INVESTIGATION OF THE CHARACTERISTICS OF KENAF FIBRE REINFORCED POLYPROPYLENE COMPOSITES

By

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DECLARATION

I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own.

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ABSTRACT

More attention has been given to biodegradable natural fibre reinforced thermoplastic composites in recent years due to stricter environmental legislations. This research work focus on the characterisation of the mechanical and thermal properties of kenaf fibre reinforced polypropylene composites.

The composites were fabricated by extrusion followed by injection and compression moulding. The effects of fibre content, coupling agent content (MAPP), different types of moulding processes and addition of filler materials (kenaf core) were observed through mechanical, thermal and microscopic testing. To investigate the mechanical properties of the composites, tensile, three point bend and Charpy impact tests were performed. The thermal properties of the composites were studied using differential scanning calorimetry (DSC). The effects of applied mechanical stresses on the samples and the resultant microstructural changes were correlated using scanning electron microscopy (SEM).

It was found that the addition of kenaf fibres improved the mechanical and the thermal properties of the polypropylene composites. Injection moulded composites with 30% fibre content modified with 4% MAPP showed the maximum tensile and flexural strength. Increasing the fibre contents to 40%, however, resulted in decreased mechanical and thermal properties due to fibre agglomeration. At this fibre loading, SEM micrographs of fractured impact test specimens showed the occurrence of interface debonding and fibre pull out. Furthermore, partial replacement of kenaf bast fibres with kenaf core fibres (bast20/core10/MAPP6%) resulted in composites with superior mechanical and thermal properties than that of the 30% bast fibre reinforced PP composites. Lastly, the flexural and impact strength of the local kenaf fibre reinforced composites were found to be comparable with that of the international (or imported) kenaf fibre reinforced PP composites.

TABLE OF CONTENT

GLOSSARY OF ABBREVIATIONS AND SYMBOLS

NFC	Natural fibre reinforced composite
MAPP	Maleic anhydride polypropylene
MFI	Melt flow index
SEM	Scanning electron microscope (microscopy)
DSC	Differential scanning calorimetry
DMA	Dynamic mechanical analyser
ESCA	Electron spectroscopy chemical analyser
IR	Infrared spectroscopy
PP	Polypropylene
LDPE	Low density polyethylene
HDPE	High density polyethylene
ABS	Acrylonitrile butadiene styrene
PVC	Polyvinyl chloride
PMPPIC	Polymethyl polyphenyl isocyanate
PS	Polystyrene
NaOH	Sodium hydroxide
Tm	Melting temperature
Tg	Glass transition temperature
Tc	Crystallisation temperature
Xc	Degree of crystallinity
ΔH_f	Heat of fusion
Wt %	Weight fraction (%)

LIST OF FIGURES

GLOSSARY OF TERMS

Composite	A material consisting of a combination of two or more materials made as one
Reinforcement	Materials added to a matrix material to improve its strength and modulus
Filler	Particles added to a matrix material, usually to improve its properties and lower the costs
Coupling agent	Physical or chemical modifier which improve adhesion between the fibre and the matrix
Adhesion	Bonding strength between the fibre and the matrix
Wetting	Filling of ridges between fibres and matrix to allow for a better bond
Interphase region	Region between the fibre and the matrix responsible for bond strength
Thermoplastic	Polymer consisting of heavily tangled molecular chains
Thermoset	Polymer consisting of a highly cross linked three dimensional network
Isotropic properties	Uniform properties in all directions
Anisotropic properties	Properties varying with direction or orientation of stress
Amorphous	Randomly set up of molecular network
Constituents	Components which make up the composite material
Failure mechanism	Ways in which composites can fail
Homogeneous	Uniform or standardised
Degradation	The breakdown or dilapidation of a material
Compounding	The process of combining things to form more intense and stronger material
Moulding	The act of creating something by casting it in a mould
Compatibiliser	Otherwise known as a coupling agent

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND TO THE INVESTIGATION

Natural fibre has been in use for over 3000 years [1]. For example, straw was used as reinforcement for clay and mud in Egypt and jute was used as reinforcement in polyester resin. Since then natural fibres are used in a variety of applications as fillers, reinforcements, insulation and for structural elements. In 2006, the European Union (EU) legislation was implemented in the automotive industry due to global warming and this has been a strong driving force for the development of biodegradable natural fibre reinforced thermoplastic composites. Several researchers [2-5] have studied the mechanical properties of the natural fibre reinforced thermoplastic composites. The effects of fibre content [2, 6, 7] and the role of coupling agents [5, 8, 9] have been well studied and published.

The automotive and aerospace industries have an urgent need for producing low density interior parts in order to reduce production costs. Therefore, the emphasis for this investigation is placed on the fabrication of kenaf reinforced PP composites, with a view to manufacturing low density composites with improved properties so that they are comparable to those achieved in a glass fibre reinforced composite. Hence, properties of the kenaf core composites require extensive research to determine the potential usages of kenaf core as reinforcing material.

Since many parameters operate simultaneously and affect the properties of composites, it is important to study the interplay between these parameters to identify the optimum processing and compounding conditions. Hence, this study focuses on the interaction between each parameter by investigating the mechanical and thermal, dynamic mechanical properties of the kenaf fibre reinforced composites as well as the morphological changes in the composite structure.

Furthermore, the mechanical properties of the kenaf core filled composites are studied to determine the potential usages of kenaf core as a filler material.

1.2 THE RESEARCH OBJECTIVE

The objectives of this project are to:

- Determine the effects of fibre content, coupling agent and addition of kenaf core on the mechanical, thermal and the dynamic mechanical properties of the composite.
- Determine the effects of different moulding processes on the mechanical properties of the composite.
- Correlate the effects of these parameters on the property changes and the resultant micro-structural changes.
- Ultimately, determine the optimum conditions to produce a kenaf fibre reinforced polypropylene composite with highly desirable mechanical and thermal properties.

1.3 THE RESEARCH METHODOLOGY

The mechanical properties of the kenaf fibre reinforced polypropylene composite was determined by analysing the results obtained from tensile, impact and three point-bend testing. The thermal properties of the composite were investigated by using the differential scanning calorimeter (DSC). Then, these results were compared with the microstructure features on the fracture surface of impact test specimens analysed by scanning electron microscopy (SEM). Other necessary information was obtained from the relevant literature.

1.4 OUTLINE OF THESIS

This thesis is divided into six chapters:

- Chapter two gives a review of literature pertaining to the research on natural fibre reinforced thermoplastic composite with particular reference to kenaf fibres.
- Chapter three describes detailed experimental techniques used in this research.
- Chapter four presents the results obtained in the form of graphs, tables and SEM micrographs.
- Chapter five gives a suitable interpretation and discussion of the results obtained.
- Chapter six draws conclusions and make recommendations from the discussion of results dealt in the chapter five.
- Chapter seven gives recommendations for future work.
- Chapter eight provides all the references and the appendices that were used in this study.

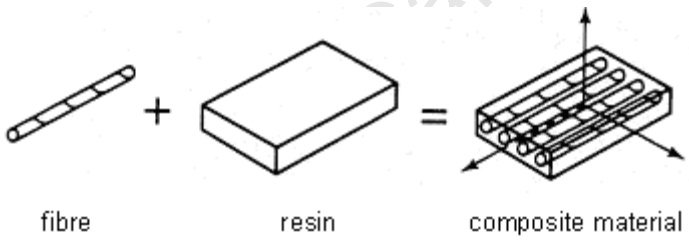
CHAPTER TWO

LITERATURE REVIEW

The present study focuses on the mechanical, thermal and dynamic mechanical properties of biodegradable kenaf fibre reinforced polypropylene composite materials. The literature review includes the properties of natural fibre and its composites, processing and applications of natural fibre composites and various analytical methods which were used to measure the properties of the composite materials.

2.1 COMPOSITES

Composites refer to the hybrid material which is made up of a polymer resin reinforced with fibres, combining the high mechanical and physical performance of the fibres and the matrix to achieve optimum properties [10].



By putting two different materials together, composites are able to compensate for the drawbacks of the individual components. For instance, as shown in the figure 2.1, composite materials can have a high stiffness and strength with a low weight as well as high corrosion resistance [10]. Furthermore, when natural or inorganic fillers are added to the composites, it results in reduced production cost.

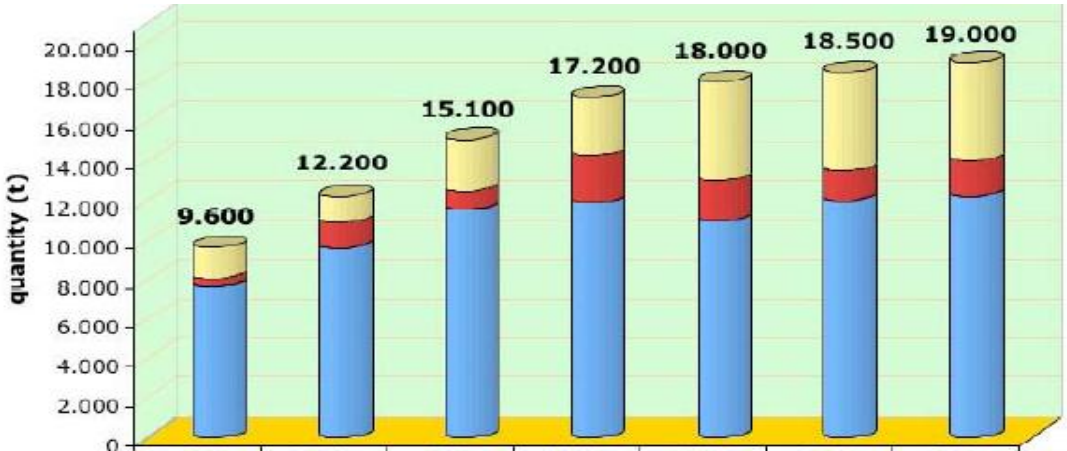
Figure 2.1 (a) Olden type of multiple part car dash board, (b) integrated same type of new composite car dash board [10]

2.2 NATURAL FIBRE REINFORCED COMPOSITES (NFC)

Natural fibres are used in a variety of applications such as fillers, reinforcements, insulation materials or structural elements. Biodegradable natural fibres have the potential to replace the conventional industrial fillers in automotive and aircraft industries due to its light weight, low production costs, high specific properties and recyclability.

In 2006, stringent European Union (EU) legislation was implemented in the automotive industry and this has been a strong driving force for the development of natural fibre reinforced composites [11]. According to EU legislation, by 2006, 80% of an automotive must be recycled and by 2015 it must be 85% [11]. As a result, most European automotive companies are making use of natural fibre reinforced composites. For example, as shown in figure 2.2, Dieffenbacher (Germany), BASF (Germany) and Rieter Automotive (Switzerland) are the leading automotive companies in Europe. Rieter Automotive produced banana fibre reinforced composites for interior parts and managed to get energy savings up to 60% or more [11]. In South Africa, the South African Council for Scientific and Industrial Research (CSIR) and the international aircraft manufacturer Airbus have formed a partnership to develop new natural fibre reinforced composite materials to be used in aircraft interiors [12].

Apart from the environmental benefits, natural fibre reinforced composites (NFC) with a high fibre content, performs the same or even better than the conventional inorganic, mineral fibre reinforced composites. Hemp fibre reinforced composites not only has environmental advantages during the production phase but also results in energy savings due to its lower weight [13]. For example, injection moulded Acrylonitrile Butadiene Styrene copolymer (ABS) four door panels weigh 9kg while the hemp fibre utilised door panels only weigh 5kg for similar mechanical properties [14].



	1999	2000	2001	2002	2003	2004	2005
Total	9.600	12.200	15.100	17.200	18.000	18.500	19.000
Exotic Fibres	1.548	1.279	2.618	2.895	4.995	5.000	5.000
Hemp	372	1.350	913	2.416	2.012	1.500	1.800
Flax	7.680	9.571	11.569	11.890	10.993	12.000	12.200

Figure 2.2 Use of natural fibres for composites in the German automotive industry 1999-2005 [15]

2.2.1 Thermoplastic Natural Fibre Reinforced Composites

The most widely used thermoplastic resin in the automotive industry is polypropylene. Polypropylene is widely used due to its low density, easy processing ability, good mechanical properties, excellent electrical properties as well as good dimensional stability [11]. The properties of common thermoplastic polymers used as matrix in natural fibre composite are listed in table 2.1 below [11].

Table 2.1 Properties of thermoplastic polymers used in natural fibre composites [11]

Properties	PP	LDPE	HDPE	PS	Nylon 6,6
Density (g/cm^3)	0.89-0.92	0.91-0.92	0.94-0.96	1.04-1.06	1.13-1.15
T_g (°C)	-10 to -23	-125	-133 to-100	100	55
T_m (°C)	160-176	105-116	120-140	110-135	250-269
Water absorption, %	0.01-0.02	<0.015	0.01-0.2	0.03-0.1	1.0-1.6
Tensile strength, MPa	26-41.4	40-78	14.5-38	25-69	12.4-94
Elastic modulus, GPa	0.95-1.77	0.05-0.38	0.4-1.5	4-5	2.5-3.9
Elongation, %	15-700	90-800	2.0-130	1-2.5	35->300
Impact strength, J/m	21.4-267	>854	26.7-1068	1.1	16-654

In order to produce a NFC with good properties, it needs to overcome two main processing obstacles. Firstly, limited processing temperature need to be solved. When natural fibres are exposed to temperatures higher than 150°C, it results in thermal degradation. Therefore, it is important to develop rapid processing techniques with low processing temperature and surface treatment [11]. Secondly, poor fibre-matrix bonding between the hydrophilic nature of natural fibre and the hydrophobic nature of polymer matrix need to be solved. The interfacial bonding strength can be improved by applying a suitable coupling agent. There are many types of coupling agents that are found. Different types of coupling agents and their mechanisms are dealt with in section 2.6. Improved adhesion by applying a suitable surface treatment enables producing of composite parts with superior mechanical properties.

2.2.2 Thermoset Natural Fibre Reinforced Composites

In the automotive industry, one of the most widely used thermoset resins in natural fibre composites is epoxy resin. This is due to its high performance as well as resistance to environmental degradation. However, it needs to overcome long curing time and high monomer cost [11]. Polyester resin is also widely used in the automotive industry. Unsaturated polyester resin is able to cure from a liquid to a solid under a variety of conditions [11]. Furthermore, vinylester resin has excellent chemical resistance, good thermal and mechanical properties, easy processing and cures rapidly. It has a better moisture resistance than the epoxies when cured at room temperature. The properties of thermoset polymers used in natural fibre reinforced composites are listed in the table 2.2 below [11].

Table 2.2 Properties of thermoset polymers used in natural fibre composites

Properties	Polyester Resin	Vinylester Resin	Epoxy
Density (g/cm^3)	1.2-1.5	1.2-1.4	1.1-1.4
Elastic modulus (GPa)	2-4.5	3.1-3.8	3-6
Tensile strength (MPa)	40-90	69-83	35-100
Elongation (%)	2	2-7	1-6
Water absorption (%)	0.1-0.3	0.1	0.1-0.4
Impact strength (MPa)	0.15-3.2	2.5	0.3

2.3 NATURAL FIBRES AS REINFORCEMENT

Due to the intensified environmental legislation as well as increasing publicity demands, automotive industries attempt to develop more environmental friendly and sustainable natural fibres reinforced composites rather than the conventional inorganic fibre reinforced composite materials. Natural fibres provide interesting properties such as biodegradability, recyclability, less abrasiveness to tooling equipment as well as low production cost. Additionally, low density natural fibres exhibit high specific mechanical properties. Because of these exceptional properties, natural fibres are used in many industrial applications especially for those industries concerned in weight reduction. For example, automotive companies and aerospace industries use natural fibre reinforced composites to produce interior components.

2.3.1 Classifications of Natural Fibre

Figure 2.3 and figure 2.4 show the classification of natural fibres. Fibres can be formed naturally or synthetically (man-made). Natural fibres can be subdivided according to their origins such as animals, plants (vegetable) or minerals. Then, vegetable fibres can be further divided into bast, leaf, seed, fruits and wood fibres. In the automotive and aerospace industries, bast and leaf fibres are most commonly used [14]. The bast fibres include kenaf, hemp and flax while sisal is considered as leaf fibre.

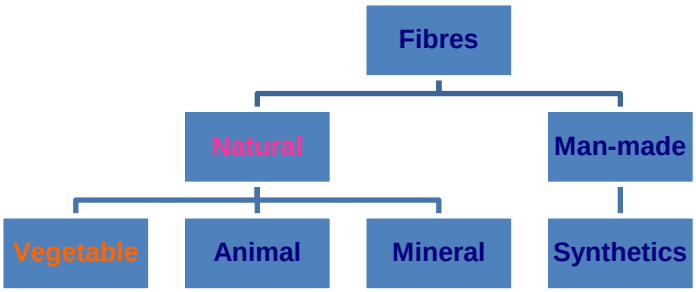


Figure 2.3 Classification of fibres

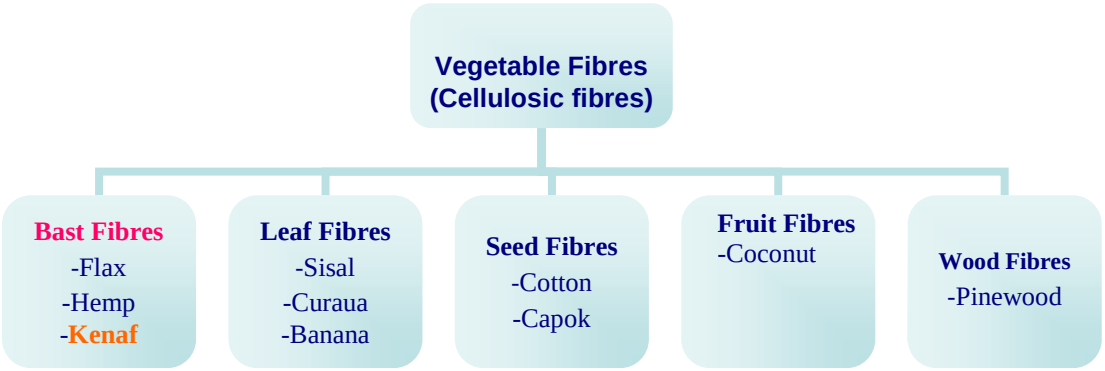


Figure 2.4 Classification of natural fibres

The fibre obtained from the outer fibrous bark is known as bast fibre. The task of the bast fibre is to stabilize the plants. It contains an inner woody core and filaments in outside. The filaments consist of cellulose, hemicelluloses, lignin and pectin. Low density bast fibres exhibit superior flexural strength and modulus of elasticity (MOE). Hence it has the potential to be used as an outstanding reinforcement in the light weight composite parts [8]. The leaf fibres show lower tensile strength and modulus than the bast fibres but it has superior impact properties [16].

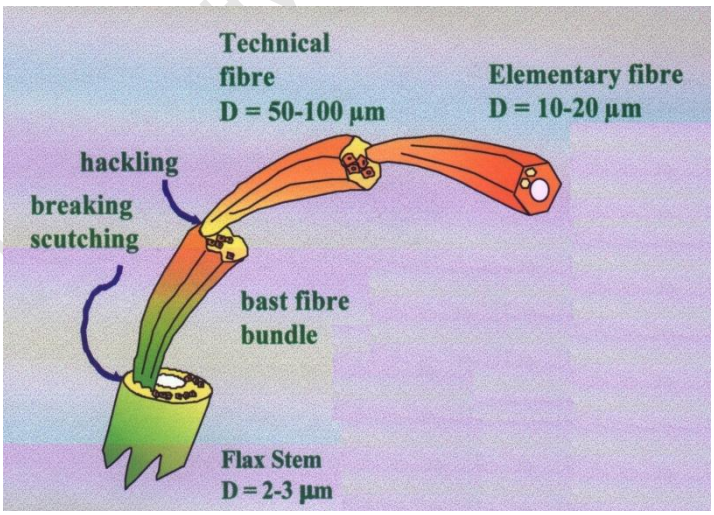


Figure 2.5 Schematic Illustration of flax fibre structure [17]

2.3.2 Advantages of Natural Fibre

Natural fibre has both ecological and economical advantages. Table 2.3 shows the comparison of properties between natural and glass fibre.

Table 2.3 Comparison between natural and glass fibres [4]

	Natural Fibre	Glass Fibre
Density	Low	Twice that of natural fibre
Cost	Low	Low, but higher than NF
Renewability	Yes	No
Recyclability	Yes	No
Energy consumption	Low	High
Distribution	Wide	Wide
CO_2 neutral	Yes	No
Abrasion to machinery	No	Yes
Health risk when inhaled	No	Yes
Disposal	Biodegradable	Not biodegradable

Generally, the substitution of glass fibres with natural fibres is based on economical benefits due to its low density and low cost. Bast fibres are abundant in many nations and its cost is significantly less than glass fibres. For instance, natural fibres cost 0.5-0.6 Euros/kg while glass fibre costs 9.0 Euros/kg [14]. Cellulosic natural fibre has a maximum density of 1.5g/cm^3 while the glass fibre has a density of 2.5g/cm^3. Due to its low component weight, natural fibre reinforced composites exhibit high specific strength and stiffness. For example, injection moulded ABS four door panels can be replaced by natural fibre utilised panels with similar mechanical properties. This replacement results in 12 to 30% of reduced weight [14]. Low density increases fuel efficiency and reduces other handling costs. Furthermore, natural fibre is less abrasive to tooling equipment so it causes relatively low wearing rates on mixing tools. It also has an excellent formability which leads to lower overall production costs. Biologically, natural fibres do not cause respiratory problems as compared to glass fibres and it does not pose biohazard on disposal [14].

The most distinctive advantage of natural fibre is its biodegradability. As shown in figure 2.6, when natural fibre is incinerated, it generates very small amounts of carbon dioxide which is neutral. Furthermore, natural fibre has good acoustic properties as well as good thermal insulation properties due to its hollow cellular structure.

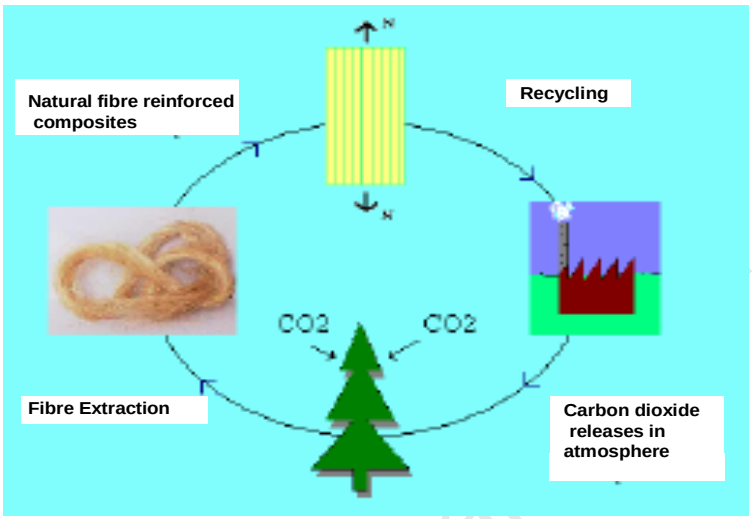


Figure 2.6 Natural fibre life cycle [17]

2.3.3 Limitations of Natural Fibre

One of the main drawbacks from using natural fibre is based on its hydrophilic nature [16]. The polar and hydrophilic nature of natural fibres results in high moisture absorption which causes loss of dimensional stability due to swelling. Due to its hydrophilic nature, natural fibres face difficulty with bonding with the hydrophobic polymer matrix. When the polar and hydrophilic nature of natural fibres is compounded with the non-polar and hydrophobic nature of polymer matrix, it could result in poor fibre-matrix interfacial bonding. In order to overcome these problems, it is necessary to introduce an effective fibre surface treatment. This will be discussed in more detail in the section 2.6. Another main problem of using natural fibres is based on its low impact strength. When a high concentration of natural fibres is added to the matrix, it gives rise to significant stress effects in the fibres and the matrix. A high proportion of fibres is failing in the crack plane during fracture. As a result, there is limited fibre pull out and dissipation of crack tip energy [14].

Furthermore, the processing temperature is limited to about 200˚C. The occurrence of fibre degradation at high temperature limits the type of thermoplastics that can be blended with natural fibres to polypropylene (PP), polyethylene (PE), polystyrene (PS) and polyvinyl chloride (PVC). Finally, since they are growing naturally, the properties of fibres can vary immensely from plant to plant [16].

2.3.4 Mechanical Properties of Natural Fibre

Table 2.4 shows a comparison between the mechanical properties of natural fibres and man-made fibres. According to Wambua [4], the mechanical properties of natural fibre reinforced composites can compare favourably with the corresponding properties of the glass fibre reinforced composites. It was shown that increasing the fibre content resulted in increased tensile and flexural properties of the composites. On the other hand, addition of natural fibres resulted in decreased impact strength compared to that of glass mat composites. This study demonstrated that the natural fibre composite has the potential to replace glass fibre composites in many applications which do not require very high load bearing capabilities. The mechanical properties of composite depend on several parameters such as fibre content, fibre orientation, fibre-matrix bonding strength and the properties of the matrix [3]. The tensile strength and modulus increase with increasing fibre volume fraction and this increment is enhanced by the use of a coupling agent since it improves the fibre-matrix adhesion and wettability.

Table 2.4 Comparison between natural fibres and man-made fibres [4]

	Fibre	**Density (g/ cm^3)**	**Elongation (%)**	**Strength (MPa)**	**Modulus (GPa)**
Natural Fibres	Sisal (Leaf)	1.5	3-7	530-640	10-22
	Hemp (Stem)	1.5	1.7	920	70
	Flax (Stem)	1.5	1.8	840	100
	Kenaf (Stem)	1.4	------	930	53
	E-glass	2.6	3.5	3400	71
Man-made Fibres	Aramid (K49)	1.4	2.5	2760	124
	Carbon fibre	1.8	1.3	3000	200

2.3.5 Applications of Natural Fibre

Natural fibres have been used since 3000 years ago [1]. For example, straw was used as reinforcement for clay and mud in Egypt. Also, jute reinforced polyester resin was used in India. In 1942, Henry Ford produced a prototype hemp fibre composite car and since then, natural fibre has been used as reinforcement for automotive interior components (see figure 2.7). However, the development of metals for construction decreased the interest in the usage of natural fibres. Only in the last 15-20 years, has NFC regained interest due to the environmental legislation and improved technology which enables the production of a natural fibre composite material with desirable properties. Since 1995, natural fibres have been widely used in the automotive industry for interior parts [18]. Currently, an average of 5 to 10 kg of natural fibres are used in the interior of European cars such as door panels, seat backs, insulating materials, parcel shelves, engine shields, bumpers, wheel arches, seat cushions and trunk liners [19].

Figure 2.7 Application of natural fibre in interior parts of automobiles [14]

For example, the Audi A2 mass produced with aluminium body and door panels are reinforced with flax and sisal mat. By using a natural fibre door panel, a 20% of weight saving is achieved [14]. According to the European Guideline 2000/53/EG, 85% of weight of the vehicle must be recycled by 2005 and this criterion will be increased to 95% by 2015 [20]. Furthermore, natural fibres are used as reinforcement in aircraft and marine structures, decking and many other applications.

2.3.6 Kenaf Fibre

Kenaf fibre is originally from West Africa and it has been cultivated since 3500 B.C [17]. Kenaf is a herbaceous plant that can be grown under a wide range of weather condition. Kenaf stalk consists of an outer "bast" fibre and an inner "core" fibre (see table 2.5). Bast fibre makes up 25% of dry weight of the processed stalk and core fibre makes up to 65%. The remaining 10% is dust and short fibres [14].

Table 2.5 Comparative properties of bast and core materials [21]

Fibrous material	**Density (g/cm^3)**		**Length (mm)**		**Diameter (um)**		**L/D ratio**	**Tensile Strength (psi)**
	Fibre	Bundle	Range	Avg	Range	Avg		
Kenaf (bast)	-	1.2	1.4-5	2.6	14-23	21	124	58,000
Kenaf (core)	0.31	-	0.4-1.1	0.6	18-37	30	20	-

As shown in the table 2.6, kenaf fibres have major advantages over rival fibre crops such as hemp, jute, flax and sisal. Kenaf fibre has a high modulus of 60 GPa due to its high cellulose content compared with the moduli of sisal, jute and flax [14]. Unlike hemp, kenaf fibre can be grown and cultivated at lower cost and it does not require a special license to grow. In addition, Parikh [14] found that the kenaf fibres blended with recycled polyester or used polypropylene could meet the industry specifications of flammability, odour, mildew and strength.

Table 2.6 The mechanical properties of kenaf vs. rival crops [14]

Lower cost	**Compared to**	Hemp
Flexibility, ease of use		Sisal
High yield, good tensile strength		Flax
High modulus of 60 GPa		Sisal = 22 GPa
		Jute = 26.5 GPa
		Flax = 27 GPa

2.3.7 Processing of Kenaf Fibre

Kenaf has been cultivated in India, Bangladesh, South Africa and Southeast Europe. SA trials indicate that one hectare will produce between 13-18 metric tonnes of raw material [14]. Kenaf can grow to about four meters in four to five months and it can yield two or three times per year in tropical climates [11]. Kenaf fibre is highly influenced by weather and soil conditions. Thus, once kenaf stalks have been harvested, it needs to undergo a certain process prior to composite processing. Kenaf harvesting and processing techniques have been investigated for many years [23, 24].

2.3.7.1 Retting

Kenaf stems consist of two types of fibres; the coarser bast fibre in the outer layer and soft, fine woody core in the inner layer. Once the kenaf plant is harvested, it needs to undergo a retting process in which the fibres are separated from the stem [11]. There are two main types of retting. The most commonly used retting process is called "dew retting". For dew retting, plant stems are left in the field for few weeks so that rain or dew break into the plant stem and separates cellulose fibres [11]. Pectin and lignin are broken by this bacterial action. It is important to monitor the retting process constantly in order to prevent severe fibre degradation by bacteria. The other retting process is called "water retting". In this case, fibres are soaked in water for a period of time to loosen the fibres from the pectin and the lignin. The ideal temperature for water retting is 34ºC and it takes between 29 to 70 hours [17]. Water retting process results in clean, uniform fibres [11]. Separation can also be done by "chemical retting". This process reduces the retting period to 48 hours and enhances the uniformity of the fibres [17]. However, it can cause a loss in tenacity, colour as compared to the bacterially retted fibres [11].

Figure 2.8 Kenaf fibre processing [14]

2.3.7.2 Decortication

Bast fibres are extracted from the plant material by a decortication process. It is important to remove the hemicellulose since it is responsible for the moisture absorption. This is done by applying hydro-thermolysis or alkali reactions [11].

2.3.8 Applications of Kenaf Fibre

Since the 1960s, extensive research work was carried out for the applications of kenaf fibre [25]. Due to a significant growth in the polymer industry as well as an intensified environmental legislation, it became necessary to introduce new types of environmental friendly fillers and reinforcements. These bio-fillers and bio-reinforcements can reduce the overall production cost and satisfy the mechanical requirements for the industrial applications of these natural fibre reinforced composite materials.

2.3.8.1 Applications of kenaf bast fibre

Kenaf is mostly used as a raw material as an alternative to wood in the pulp and paper industries [2]. Research has shown that the chemi-thermomechanical pulp which is made from the whole stalk of kenaf can be used to manufacture a high quality paper [14]. Unlike wood pulp, kenaf pulp is whiter, stronger, smoother and has a better ink retention [26]. Along with development of processing technology, kenaf bast fibres are widely used as reinforcement in composites. According to the research work done by Rowell et al [7], kenaf fibre reinforced polypropylene composites can be used as an alternative reinforcement to inorganic / mineral based composites.

As with the other natural fibres, kenaf fibre demonstrates low density, high specific mechanical properties, non-abrasiveness during processing, biodegradability and recyclability [16]. Due to these advantages, kenaf is widely used as reinforcement in the automotive industry. It was found that the interior automotive trim which were made of kenaf bast fibre have many advantages. For instance, the tensile modulus and impact strength of kenaf reinforced composites were well comparable or even superior to that of the glass fibre reinforced composites [4].

2.3.8.2 Applications of kenaf core fibre

Kenaf core contains a sponge like structure in the central part which is called pith. Kenaf pith has a high absorption ability. This unique physical structure of kenaf core enables the material to absorb up to 4 times its specific weight, as apposed to that of 2.5 times of the woodchips and the shavings [14]. Thus, kenaf core is used to absorb, drain and neutralise liquids, sewage and chemical / oil spills. Kenaf core fibres appear to be a potential raw material for the low density panels which are excellent for sound absorption and thermal resistance [25]. Kenaf core panels would make excellent ceiling tiles, decorative panel substrates, floor tile substrates and elements of certain structural components. Furthermore, kenaf core can be used as filler for plastics, paints, pharmaceuticals, and cosmetics. Recent research work done by Jacobson et al [25] found that the mechanical properties of the kenaf core filled polypropylene composites are equivalent to that of talc, calcium carbonate or wood flour filled polypropylene composites for industrial applications where water absorption is not a problem.

Figure 2.9 Applications of kenaf core fibre [14]

2.4 POLYMER MATRIX IN COMPOSITES

2.4.1 Functions of the Matrix

To achieve successful a compounding process, there are three important features which need to be considered. Firstly, the matrix must have good mechanical properties such as high ultimate tensile strength and high stiffness. It is also crucial to have high failure strains to prevent composites from the brittle fracture. Secondly, the matrix must have good adhesive properties. Strong adhesion between the matrix and the fibre is very important for efficient stress transfer and to prevent the fibres from debonding or cracking. Furthermore, the matrix must have good resistance to environmental degradation. The matrix must be able to protect the fibres from harmful environmental (corrosion resistance) and other aggressive substances [17].

2.4.2 Thermoplastic Matrix

The polymer matrix can be divided as thermoplastics and thermosetting. The mechanical properties of some of the most commonly used matrices are listed in the table 2.1 and table 2.2. Thermoplastic matrices haves some superior properties to thermosetting matrices. A thermoplastic matrices exhibits higher fracture toughness, no chemical reactions during processing, unlimited shelf life, easy storage, fast and easy processing as well as recyclability. However, it has poor fatigue performance and a relatively high viscosity.

2.5 NONWOVENS

According to Gillies [27], non-wovens can be defined as the structures which consist of a web of fibres joined by chemical or mechanical means. It also can be defined as a textile structure made directly from fibre rather than yarn [28]. Recently, many of the woven and knit materials are replaced by the non-woven products due to its lower density and lower cost. Non-woven products are predominant in the automotive industries and the geo-textile industries because of their higher permeability, better friction, better conformability and higher construction survivability compared to that of the woven products [6]. There are numerous applications where the non-woven materials are utilized, ranging from baby diapers to industrial high performance textiles. Some of the important areas where the non-wovens are treated as a primary alternative to the traditional textiles are geo-textiles, materials for building, thermal / sound insulating materials and hygienic/ health care textiles. Non-wovens are also used in agriculture, aerospace and home furnishings.

In most cases, non-wovens are made by producing a web of fibres, which are then strengthened by the various bonding techniques. Briefly, there are three ways that the non-woven webs can be formed. (1) Through air laid, fibre webs are formed as the fibres are opened and suspended. Then the fibre webs are collected on a moving screen. (2) In wet laid, a mixture of fibres in water are collected on a screen then drained followed by drying. (3) In spun laid, hot and continuous synthetic filaments are extruded through a spinneret. Then the filaments are blown onto a moving belt where they are bonded together by themselves to form a web [6].

Once the fibre webs are produced, they are strengthened by the traditional and the mechanical bonding techniques such as thermal bonding, hydro-entanglement and needle bonding. Bonding of the thermoplastic non-woven can be done by the application of heat, called thermo- bonding. In hydro-entanglement, fibres are bonded by entangling, using very fine jets of high pressure water. Needle bonding is performed by entanglement of the fibres by a set of barbed needles punching through the webs [28].

2.6 FIBRE-MATRIX ADHESION

The interfacial bond strength between the matrix and the fibre has a significant effect on the end use of natural fibre reinforced polymer composites. As mentioned earlier, the hydrophilic, polar nature of natural fibres adversely affects the adhesion to the hydrophobic, non-polar nature of the polymer matrix. In other words, it is difficult to blend and compound the natural fibres and the thermoplastic matrix due to the poor compatibility between them [28]. Poor adhesion at the interface region interrupts a stress transfer from the matrix to the fibre. As a result, poor adhesion may cause a loss of strength. In addition, poor adhesion between the matrix and the fibre causes moisture absorption during the compounding and moulding process. This results in swelling and cause dimensional instability. Hence, in order to reach the full commercial potential of the natural fibre composite material, the fibres need to be modified to improve their surface properties [5].

2.6.1 Chemical Modification of Fibres

The hydrophilic nature of natural fibre is a major drawback to their use as reinforcement. Since natural fibres contain many hydroxyl groups on their surface, it easily reacts with water. This causes a poor interfacial bonding with the polymer matrix and could results in a loss of dimensional stability. This may lead to the degradation of mechanical properties of the composites. Several methods have been proposed to improve the adhesion between the fibre and the matrix by applying chemical or physical modifications. Mwailkambo and Ansell [29] studied the effects of chemical treatment on the hemp, jute, sisal and kapok fibres with various concentrations of NaOH. It was found that 6% of NaOH was the optimum concentration in terms of cleaning the fibre bundles surfaces and retaining a high index of crystallinity. Kostic et al [30] studied the effects of chemical modification on hemp fibres. Hemp fibres were modified by treating with NaOH solutions. As shown in the table 2.8, after treatment, the weight loss of hemp fibres was clearly visible. This weight loss was due to the solubilisation of the hemicelluloses and part removal of the lignin from the hemp fibres [30].

Increasing the NaOH concentration accelerated the removal of the non-cellulosic substances and increased the fibre liberation.

Table 2.8 Chemical composition and weight loss of hemp and modified hemp fibres [30]

Concentration of NaOH	Temperature	A-Cellulose Content (%)	Lignin Content (%)	Hemicellulose Content (%)	Weight Loss (%)
Unmodified sample	----------	76.12	5.65	12.28	--------
5%	Room temp	82.43	4.10	9.07	3.5
5%	Boiling temp	89.16	2.88	4.84	18.8
18%	Room temp	83.44	2.66	6.09	8.3

The reduced content of hemicelluloses represents the removal of the components which make fibres stiff and difficult to process [30]. However, there are still certain amount of hemicellulose remained in the structure due to the strong hydrogen bond between hemicellulose and cellulose fibrils. According to Wang et al [9], lignin cannot be completely removed by the alkali treatment due to the presence of strong carbon-carbon linkages and the presence of many aromatic groups in the structure which provides a strong resistance to chemical attack. The effects of chemical modification on hemp fibre to the tenacity, flexibility and water retention values are shown in the table 2.9 below [30].

Table 2.9 Tenacity, flexibility and water retention values of hemp fibres [30]

Concentration of NaOH	Tenacity (cN /tex)	Flexibility (cm)	Water retention value (%)
Unmodified sample	23.6	4.30	48.9
5% (room temp)	34.3	4.42	40.2
5% (boiling temp)	30.4	4.80	34.8
18% (room temp, slack)	12.3	6.05	36.8
18% (room temp, tension)	36.2	1.30	41.9

According to Wang et al [9], there was a significant increase in the tensile strength of the modified hemp fibres. However, an 18% NaOH treated hemp fibre under slack condition showed a 48% drop in tenacity. The significant decrease in tenacity is due to the removal of hemicelluloses accompanied by swelling and shrinkage of ultimate cells, which resulted in some disorientation of the fibrils. The disorientation of the fibrils caused poor and ineffective stress transfer among the fibrillar network [30]. On the other hand, hemp fibre treated with 18% NaOH solution under tension showed a significant increase in the tensile strength. The main reason for this is the removal of inter-fibrillar regions which are less dense and rigid. Thus, the fibrils are more capable of rearranging along the direction of tension [30]. The alkali treated hemp fibre shows a higher flexibility except for the fibres treated with 18% NaOH under tension. A change in flexibility is due to the partial removal of lignin and hemicellulose.

Edeerozey et al [8] have treated kenaf fibres with the NaOH solutions of different concentrations. In their study, tensile strength tests were performed on fibre bundles. The maximum breaking load was determined directly from the stress- strain curve and the unit break (UB) was calculated as follows [9]:

$$UB=F/d$$

Where F= maximum breaking load (N), d= cross-sectional area of the fibre (mm^2)

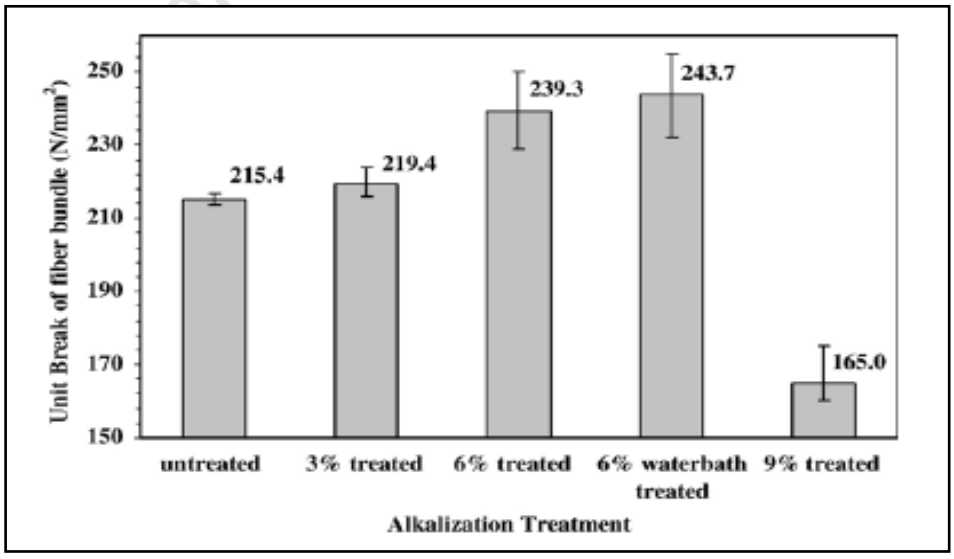


Figure 2.10 Average unit break of kenaf fibre bundles [8]

From the fibre bundle test results, kenaf fibres treated with 6% NaOH in a water bath (at 95^0C) showed the highest value of unit break followed by 6% NaOH at room temperature. This is because of more effective cleaning process at higher temperature as compared to the room temperature condition. However, there was a significant decrease in the average unit break value when the fibre was treated with 9% NaOH solution. The concentration of NaOH could be too strong and might have damaged the fibres, thus resulted in a lower tensile strength [8]. Scanning electron microscope provides information of the surface morphology of untreated and treated kenaf fibres.

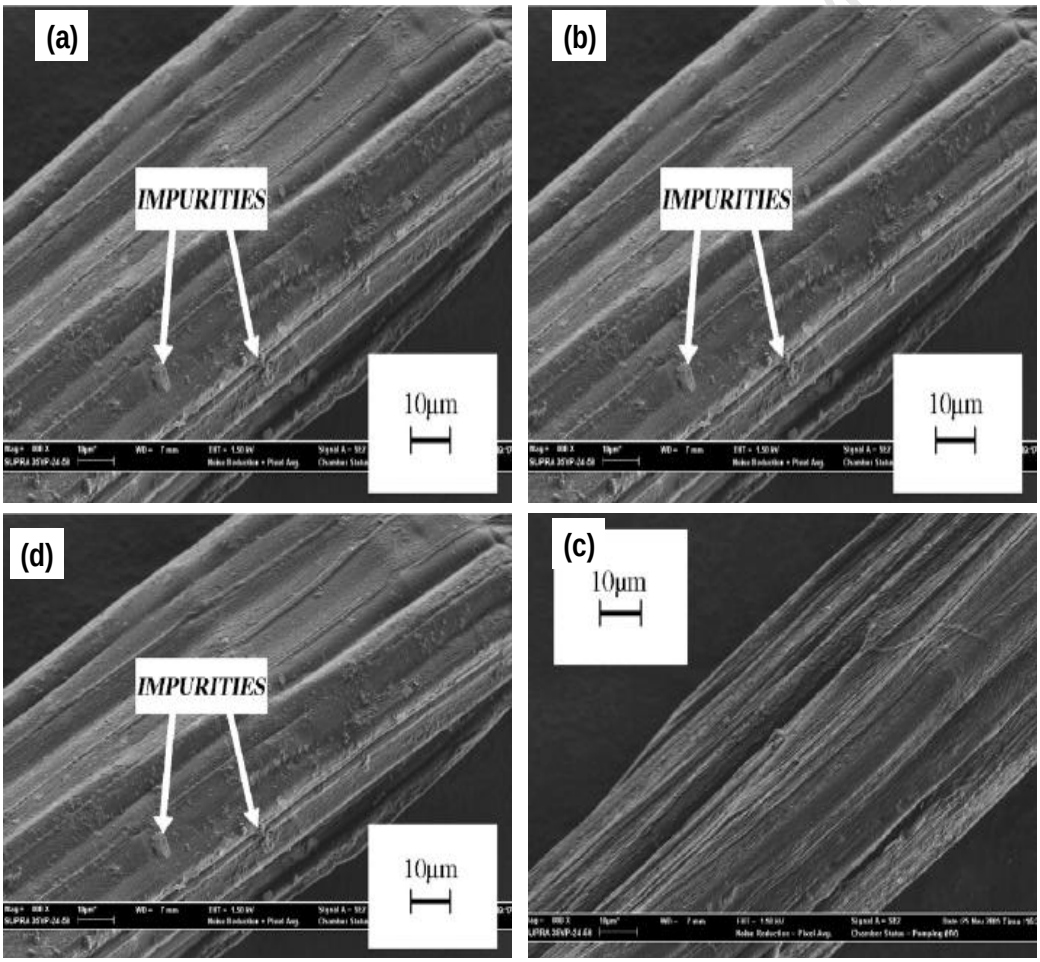


Figure 2.11 SEM micrograph of (a) untreated kenaf fibre and (b) 3% NaOH treated kenaf fibre and (c) 6% NaOH treated kenaf fibre and (d) 9% NaOH treated kenaf fibre [8]

Figure 2.11 (a) shows the SEM micrograph of an untreated kenaf fibre. As expected, there were impurities on the fibre surface. In (b), impurities can still be observed; therefore 3% NaOH was not good enough to effectively remove the impurities from the fibre surface. A SEM micrograph of 6% treated kenaf fibre surface (c) shows almost complete removal of impurities on the fibre surface. When fibre was treated with 9% NaOH, the SEM micrograph shows the absence of impurities on the fibre surface but looks jagged and rough [8].

2.6.2 Surface Modification

Many types of additives have been studied to improve the dispersion and the interaction of natural fibre reinforced composites [31, 32]. Applications of suitable physical (e.g. corona discharge) and chemical surface treatment methods (e.g. coupling agents such as silanes and MAPP) will result in better surface properties of fibres [33]. According to Felix et al [34], cellulose fibres show significant differences in surface energy values between the MAPP (maleic anhydride polypropylene) treated fibres and untreated fibres. Maleic anhydride (MA) grafted polypropylene (MAPP) has been reported that it functions efficiently for kenaf / PP composites [35]. Better cooperative interaction and adhesion at the fibre-matrix interface lead to the decrease in water absorption and improve the stress transfer.

2.6.3 Properties Affecting the Fibre-Matrix Adhesion

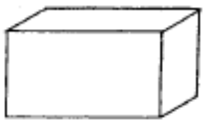
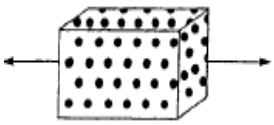
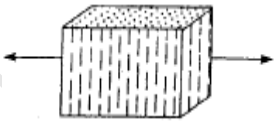
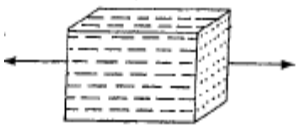
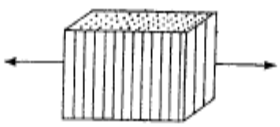
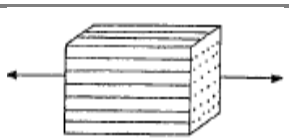
Unlike metallic composites, fibre reinforced polymer composites are heterogeneous and the individual laminas are structured in an anisotropic way. The internal structure of composites can be observed in the damaged zone, generally in the fibre-matrix interphase region. The mechanical properties of composites not only depend on the constituents (fibre and matrix) properties, but also on the fibre-matrix interfacial bonding strength [36]. The strength of interface adhesion is directly related to the ability of load transfer from the matrix to the fibres. Thus, fibre-matrix adhesion is an important factor influencing the mechanical properties of the composites.

The fibre-matrix interface properties are influenced by polymer morphology, extractive chemicals, strain rates and processing conditions [33].

2.6.3.1 Fibre Orientation Distribution

It was found that the fibre orientation distribution is one of the most crucial variables which determine the mechanical properties of short fibre reinforced composites [37]. By changing the orientation or placement of the fibres, the material can be designed to exhibit properties that are isotopic or highly anisotropic depending on the desired end results. The table 2.10 shows the effects of fibre orientation on the strength and stiffness of the composites.

Table 2.10 Experimental stress-strain data for a variety of glass/epoxy systems [37]

Stress Direction	Filler shape and orientation	Strength (10^3psi)	Stiffness (10^6psi)	Ultimate Strain (%)	Volume Fraction filler, V_f
Unfilled resin		10-12	0.3-0.4	4-5	0
Bead filled		9-10.5	1.5-1.7	2.0-2.5	0.5
Short fibres (transverse)		5.5	1.4	0.4-0.5	0.5
Short fibres (longitudinal)		40	4.5	0.6-1.0	0.5
Continuous fibres (transverse)		4-6	1.8-2.1	0.4	0.6
Continuous fibres (longitudinal)		130-160	6.3-6.8	2.0	0.6

Composites with fibres orientated in the longitudinal direction shows higher strength, stiffness and failure strain than that of the composites with fibres orientated in the transverse direction. Joseph et al [38] reported that unidirectional alignment of short fibres is achieved by the extrusion process. The tensile strength and modulus of the composites along the axis of the fibre alignment are enhanced by more than two fold compared to the randomly oriented fibre composites [38]. The viscoelastic and rheological properties of short sisal fibre reinforced LDPE composites were also investigated in their studies. They have reported that the longitudinally oriented composites showed the maximum storage modulus. Randomly orientated fibres have provided a good formability, but without good directional properties. The more formable sheets can be produced by using aligned, discontinuous fibres than continuous fibres [16]. As shown in the figure 2.12, when the fibres are added in a perpendicular direction to the plain matrix material, the specimens become weakened [3]. The tensile and impact strength of the unidirectional fibre reinforced materials showed the highest value which has a potential to be used as an effective reinforcement [3].

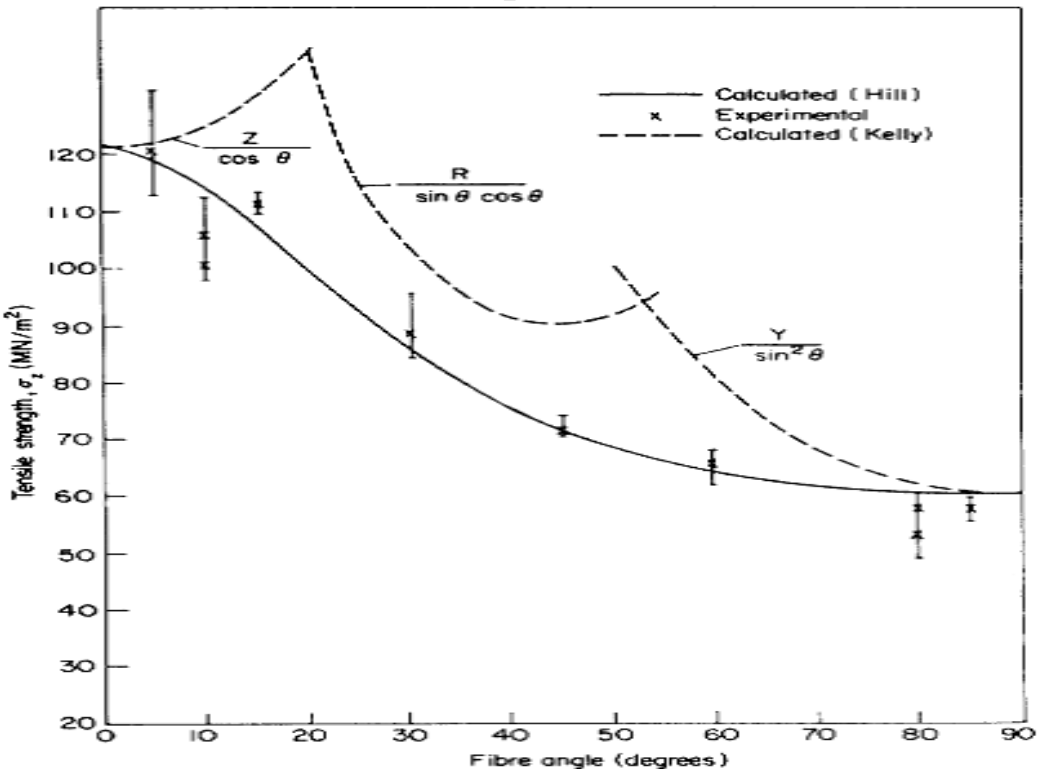


Figure 2.12 Tensile strength of glass fibre reinforced (29.2 W_f %) PMMA as a function of fibre orientation [3]

2.6.3.2 Fibre Length

Common difficulties have been shown with the forming of straight, continuous fibre or woven fibre composite sheets due to wrinkling of the fibres or distortions. Randomly orientated fibres have provided good formability, but without the advantage of the highly directional properties often desired in composite parts. Although, long continuous fibres are more efficient in reinforcing the material, they need more expensive and complicated processing methods. Sometimes, it is impossible to use long fibres in a thermoplastic matrix because the viscosity is too high [3].

2.6.3.3 Fibre Contents

Table 2.11 shows tensile strength, stiffness and failure strain of the sisal fibre reinforced polypropylene (PP), polystyrene (PS) and low density polyethylene (LDPE) matrix composites. The tensile strength and the modulus increases as the percentage of fibre contents increases from 0 to 30%. Since PP is more crystalline than LDPE, the increase in tensile strength by the addition of sisal fibre is less in the case of PP compared to LDPE [39].

Table2.11 Comparison of the tensile properties of longitudinally and randomly oriented solution mixed sisal fibre reinforced PP, PS and LDPE [39]

Fiber Content (%)	Composite Type	Tensile Strength (MPa)		Young's Modulus (MPa)		Elongation at Break (%)	
		L	R	L	R	L	R
0	PP	35.00	35.00	498	489	15.00	15.00
	PS	34.90	34.90	390	390	9.00	9.00
	PE	9.20	9.20	140	140	200.00	200.00
10	PP	36.00	29.00	730	605	7.82	8.00
	PS	21.30	18.16	629	516	9.00	7.00
	PE	15.61	10.80	1429	324	4.00	27.00
20	PP	39.10	31.14	971	798	7.11	7.33
	PS	43.20	25.98	999	553	8.00	6.00
	PE	21.66	12.50	2008	453	3.00	10.00
30	PP	44.40	33.84	1040	940	8.33	8.50
	PS	45.06	20.42	9998	624	7.00	4.00
	PE	31.12	14.70	3086	781	2.00	7.00

Figure 2.13 shows stress-strain curves of a kenaf fibre reinforced polypropylene composite. Kenaf fibres were modified by 2% by weight of MAPP. Increasing the amount of kenaf fibre in the composites resulted in the increased tensile strength. The tensile strength of unfilled PP and uncoupled composites were very similar, regardless of the amount of fibre present. This was caused by very poor stress transfer from the matrix to the fibre due to the incompatibility at the interface region [7]. As expected, the failure strain decreases with increasing amount of kenaf fibres. The nonlinearity of the curves is mainly due to the plastic deformation of the matrix [35].

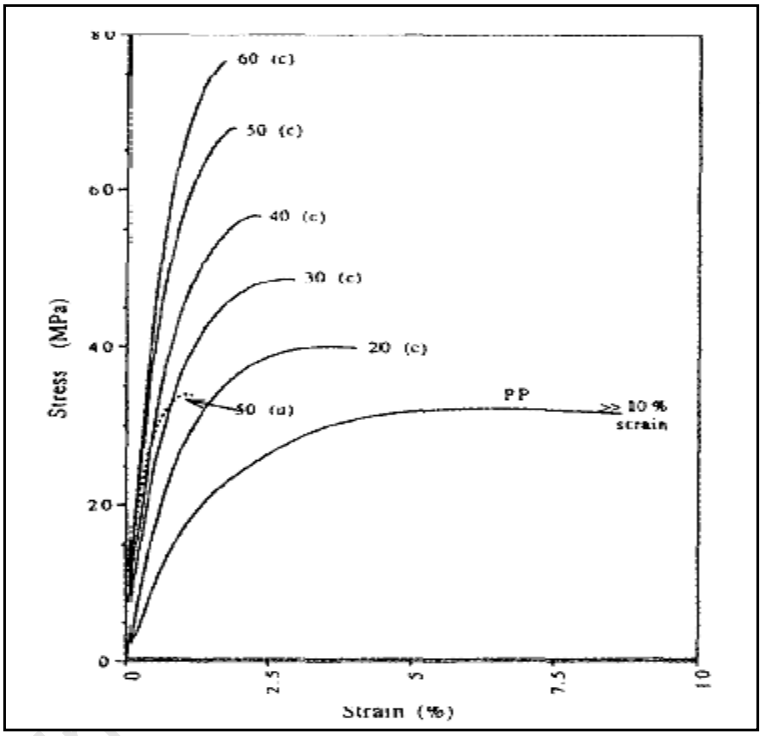


Figure 2.13 Stress-strain curves of kenaf filled composites [7]

According to Sanadi [35], the tensile modulus and the flexural modulus showed significant improvement with the addition of fibres. The impact strength is affected by the fibre content and the type of testing. In the case of notched samples, the impact strength increases with increasing amount of fibres. The fibre bridges the crack and increases the resistance to propagation of the crack. In the case of un-notched samples, the impact values decrease with the addition of fibres. This is because the addition of the fibres creates regions of stress concentrations which require less energy to initiate a crack [35]. It was demonstrated that as the fibre volume fraction is increased, a matrix dominated failure mode increases [36].

2.6.3.4 Coupling Agent Contents

Georg et al [40] attempt to solve the problem of fibre-matrix adhesion by applying alkaline solution to the fibres. Natural fibres are mainly composed of cellulose, whose elementary unit is anhydro d-glucose. This unit contains three hydroxyl groups. Hydroxyl groups cause all vegetable fibres to be hydrophilic and form intermolecular and intermolecular bonds with water. The alkaline solution regenerates the lost cellulose and dissolves unwanted microscopic pits or cracks on the fibres, resulting in better fibre- matrix adhesion [40].

Several studies [41, 42, 43] have reported the influence of chemical treatment on the thermal and mechanical properties of the sisal fibre reinforced thermoplastic composites. Joseph et al. [41, 44] investigated the effect of chemical treatment on the tensile, dynamic mechanical, electrical and ageing properties of short sisal fibre reinforced LDPE composites. The effects of various chemical treatments on the tensile properties of the sisal fibre reinforced LDPE composite are presented in Table 2.12.

Table 2.12 Variation of tensile properties of sisal/LDPE composites with different fibre treatment (fibre content 30%, fibre length 5.8mm) [39]

Composites	Tensile Strength (MPa)	Modulus (GPa)	Elongation at Break (%)
Untreated	31.12	3068	2
Alkali treated	34.27	3328	1
Isocyanate treated	41.50	4066	4
BP treated	40.90	4018	3
DCP treated	41.80	4156	4
$KMnO_4$ treated	38.80	3816	3

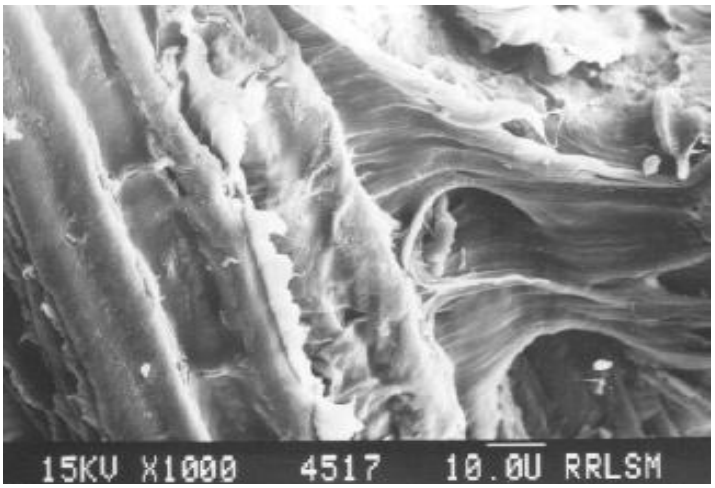


Figure 2.14 Interfacial adhesion of the chemically treated sisal/LDPE composites[39]

The dynamic mechanical properties of composites are also influenced by chemical treatment. Figure 2.15 shows the storage modulus of 20% fibre loaded sisal-PP composites. An improvement of the storage modulus was observed when the sisal fibres underwent chemical treatment. Surface modification improves the interfacial stiffness by providing more intense fibre-matrix interaction which in turn causes less molecular mobility in the interfacial region [45].

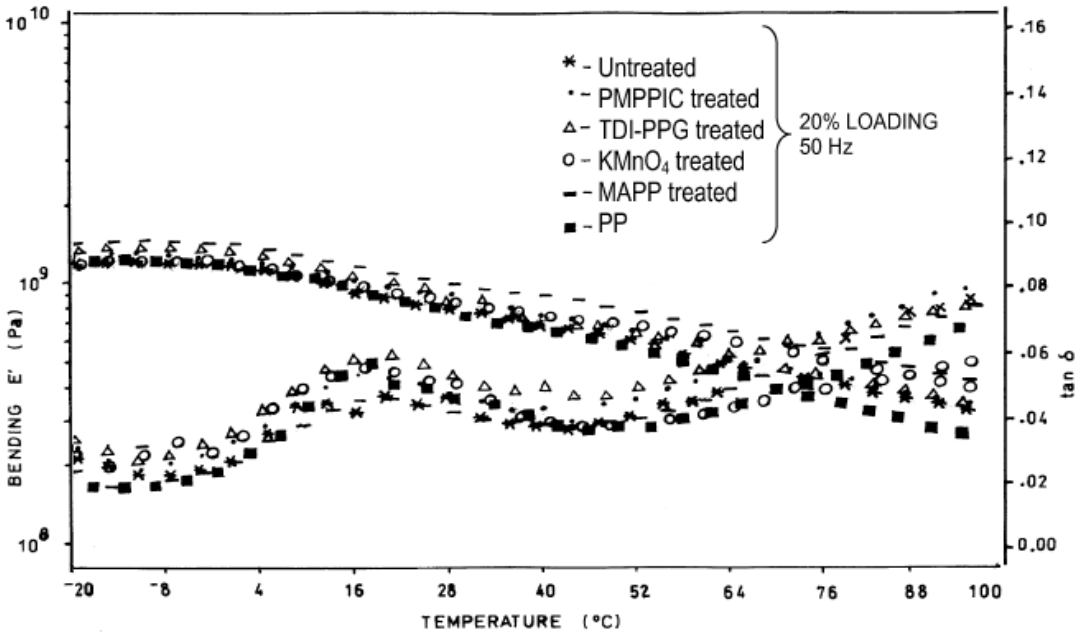


Figure 2.15 Effects of chemical treatments on the storage modulus and tan δ of sisal-PP composites at 20% fibre loading at a frequency of 50 Hz [45]

2.6.3.5 Moulding Process

According to Li [42], injection moulding is a suitable procedure to produce a natural fibre reinforced polymer composite into 3-dimensional sophisticated parts. During processing of sisal fibre reinforced polypropylene composites, the following problems were encountered. Firstly, as sisal fibres were fed into the mould, the melt viscosity of sisal fibre reinforced PP composites increased which led to poor interfacial bonding between the sisal fibre and the PP matrix. The high melt viscosity can be overcome by elevating the injection temperature but it can cause severe thermal degradation on the fibre. Influence of moulding process is dealt in more detail in the section 2.7.

2.6.4. Physical Surface Modification Treatment

Physical treatment changes the structure and the surface properties which affects the bonding of the composites. Physical treatment, however, such as stretching, calandering and thermo- treatment does not affect the chemical properties of the composites [33]. Electric discharge (e.g. corona, cold plasma) is another way of physical treatment [33]. Corona treatment is used for surface oxidation activation and it changes the surface energy of the cellulose fibres [46]. This method has been recognised as efficient cellulose fibre modifications for polystyrene, polypropylene and polyethylene. It decreases the melt viscosity of cellulose polyethylene composites [3] and improves the mechanical properties of cellulose polypropylene composites [47].

2.6.5 Chemical Surface Modification Treatment

A better compatibility between the matrix and the fibre can be achieved by the impregnation process. In a review report by Bledzki and Gassan [33], excellent partitioning can be formed between the cellulose fibres and the polystyrene resin by impregnating the cellulose fibres with a butyl benzyl phthalate plasticised PVC. This significantly lowers the viscosity of the composites and results in better cooperation between PVC and PS [28].

Coupling agents have properties between the matrix and the fibre. There are several ways that coupling agents operate [48]. Coupling agents eliminate weak boundary layers while producing tough, flexible layers. Coupling agents create a highly cross-linked interphase region by either forming covalent bonds with both matrix and fibre or by acid-base interaction at the interface through altering the acidity of the substrate surface [33]. Furthermore, coupling agents improve the wetting between polymer and substrate [33].

It has been reported that maleic anhydride (MA) grafted polypropylene (MAPP) functions efficiently for natural fibre reinforced polypropylene (PP) composites [2, 8, 16]. In order to obtain an efficient stress transfer, two factors are needed to be considered. Firstly, the amount of maleic anhydride (MA) is important. The MA present in the MAPP provides the polar interaction through the acid-base interaction. Also, MA can covalently link to the hydroxyl group on the lingo-cellulosic fibres [7]. According to Han et al [49], due to the thermodynamic segregation, the MAPP is localised on the polar cellulosic fibre surface. In the report by Felix et al, electron spectroscopy chemical analysis (ESCA) also shows the concentrated distribution of MAPP on the fibre surface [34]. The formation of covalent linkages between the MA and the hydroxyl group of lingo-cellulosic fibre are detected by ESCA and infrared (IR) spectroscopy [46]. It can be concluded that when sufficient amount of MA is present on the MAPP, strong fibre surface interphase interaction can be obtained.

Secondly, the polymer chains of MAPP should be long enough to permit the entanglements with PP matrix at the interphase [35]. The efficiency of interaction between the non-polar PP matrix and the coupling agent depends on chain entanglement. Chain entanglements help the transfer of stress from one chain to another entangled chain. These entanglements act as a cross link that provide some mechanical integrity up to the glass transition temperature, Tg, but become ineffective at much higher temperature [7, 50]. When the polymer chains are longer, there is more chance for entanglements between the chains to occur.

Hence, MAPP that has a high MA content coupled with a relatively high molecular weight will result in efficient composites [7, 35]. In other words, long chains of MAPP with the sufficient amount of MA would be the ideal additive in kenaf fibre reinforced PP composites since it forms both strong covalent bonds and many molecular entanglements that improve the interface bonding. However, extremely long chains will result in composites with lower properties since the movement of MAPP at the fibre surface becomes difficult due to the short processing periods.

As mentioned earlier, coupling agents reduce the number of hydroxyl group on the fibre surface which react with water. Hence, coupling agents are able to reduce moisture absorption and increase the wettability by forming a strong covalent bond between the matrix and the fibre. There are various types of coupling agents as presented below.

2.6.5.1 Graft Copolymerisation

Cellulose fibres are treated with an aqueous solution and are exposed to high energy radiation resulting in the formation of free radicals. Then these radical sites are treated with a suitable solution which is compatible with the matrix such as polyvinyl monomer, polystyrene or acrylonitrile [33].

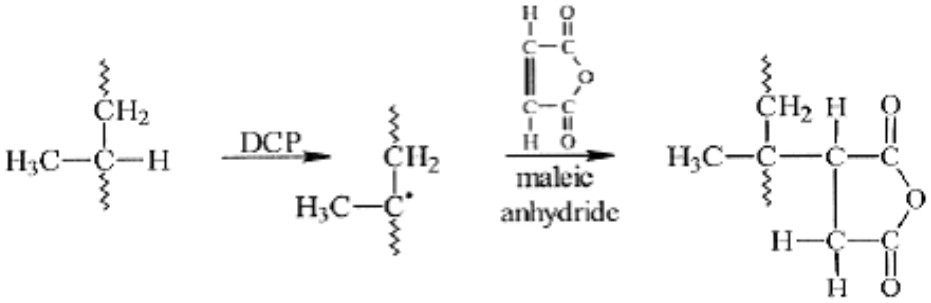
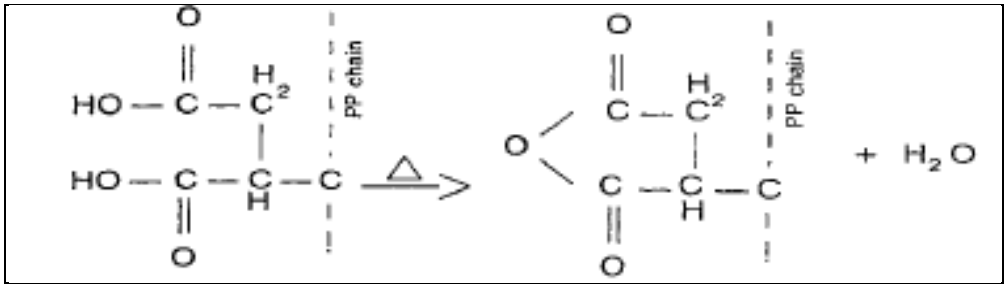


Figure 2.16 Formation of MAPP [33]

For example, treatment of cellulose fibres with the MAPP results in the formation of covalent bonds across the interface (see figure 2.17). The surface energy of cellulose fibres becomes closer to the surface energy of the matrix [33]. Thus, better adhesion and wettability are obtained.

- Activation of the copolymer by heating at 170˚ C



- Esterification of cellulose

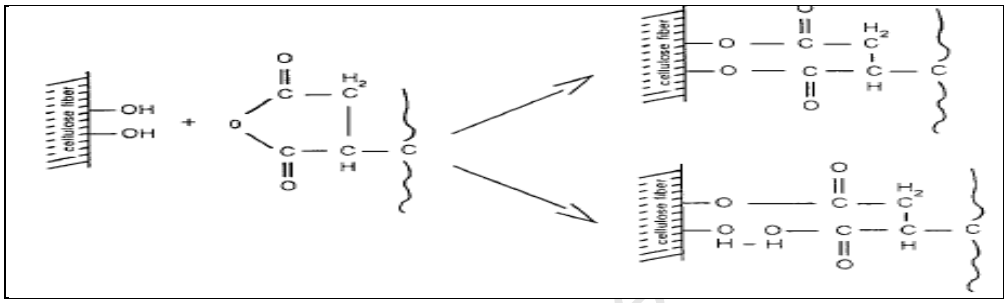


Figure 2.17 Graft copolymerization [33]

2.6.5.2 Treatment with methanol groups

When the chemical compounds containing methanol groups are treated with cellulose fibres, strong covalent bonds as well as hydrogen bonds can be formed. For example, treatment of cellulose fibres with methanol melamine compounds before the forming of polyesters composites is able to decrease the moisture absorption and increases the wettability [51].

2.6.5.3 Treatment with isocyanates

The mechanical properties of cellulose fibre reinforced composite is improved by an isocyanated treatment. For example, when polymethylene polyphenyl isocyanate (PMPPIC) is covalently bonded to the matrix, higher interfacial bonding between the cellulose fibre and the matrix is achieved. As shown in figure 2.18, both PS matrix and PMPPIC contain the benzene rings and their delocalised electrons (π) provide strong interactions, so that the adhesion between the PMPPIC and the PS is improved [33].

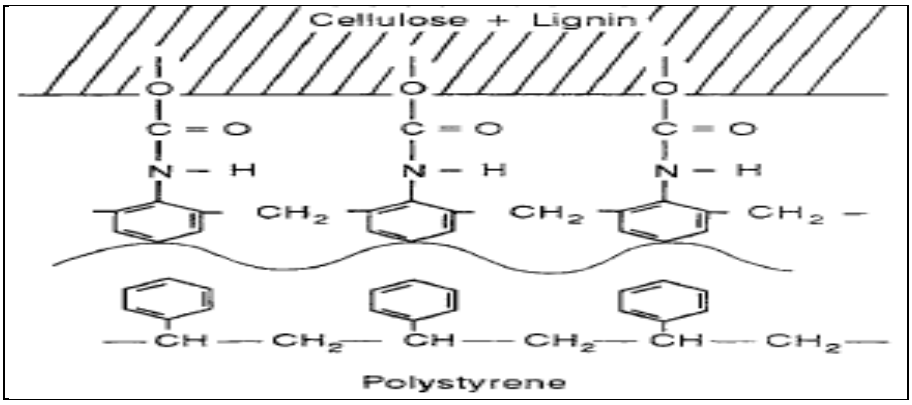


Figure 2.18 Interactions between PMPPIC and PS [33]

2.6.5.4 Triazine coupling agents

Triazine coupling agents are covalently bonded to the cellulose fibres which reduce the moisture absorption. This is done by triazine coupling agents reducing the number of cellulose hydroxyl groups on the fibre surface which reacts with moisture. Coupling agents also reduce the swelling of fibres by creating a covalent cross linkage between the matrix and the fibre [33].

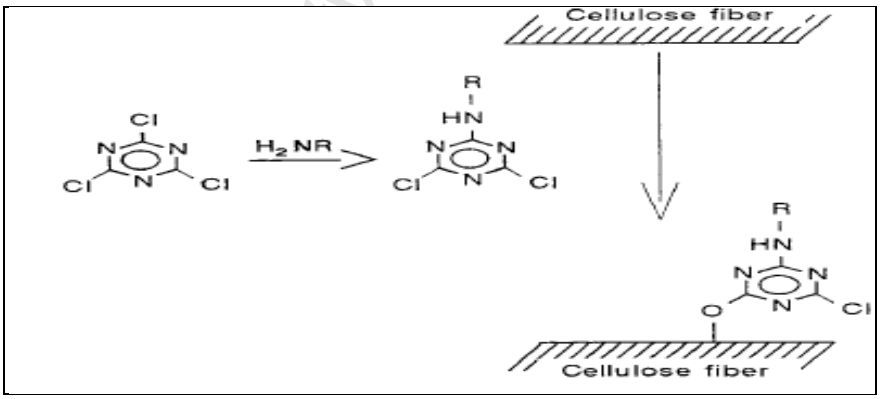


Figure 2.19 Triazine coupling agents [33]

2.7 COMPOSITE FABRICATING PROCESS

2.7.1 Injection Moulding vs. Compression Moulding

Extrusion followed by injection moulding improves fibre dispersion in a composite and hence increase the tensile and flexural properties [53]. This process, however, can damage the properties of fibres, which result in changes in the length and the diameter distribution of the fibres. Consequently, the properties of the composites materials are affected [54].

On the other hand, compression moulding neither damages nor changes the orientation of the fibres during processing. Hence, it manages to preserve the isotropic properties of the composites. It reduces the changes in physical properties which derived from the molecular relaxation of the materials during usage [54]. The properties of the compression moulded composites are related to the consolidation of composites, which depends on the processing conditions as well as the types of moulder used during processing. For instance, more pressure is transferred to the composite in a closed mould process than in a frame mould process [54].

2.7.2 Optimal Fabrication Process of Kenaf Fibre Reinforced Polypropylene Composites

One of the main obstacles that need to be addressed in the fabrication of kenaf fibre reinforced composites regards uneven fibre distribution. It was proved that using a method to chop and shift the individual fibres in a random orientation might create the fabrication of the kenaf fibre-reinforced thermoplastics with an even fibre distribution [16]. The optimal fabrication method for the compression moulding process has proven to be the layered sifting of micro fine PP powder and chopped kenaf fibres. A fibre content of both 30% and 40% by weight has been proven to provide adequate reinforcement to increase the strength of the PP powder [16]. In order to utilize the optimized process for a larger sample, six times the amount of each of material must be used [16].

In order to improve wetting between the fibre and the matrix, a coupling agent need to be applied. The coupling agent, MAPP, has been previously used in a study of maleated polyolefin coupling agents for the agro-fibre composites and has been proven to increase the flexural and the tensile strength [16].

2.8 ANALYSIS OF PROPERTIES OF POLYMER COMPOSITES

2.8.1 Tensile Analysis

Through tensile testing, the Young's modulus of elasticity, tensile strength and elongation of failure can be measured. Young's modulus indicates the load carrying ability of fibres and matrix before plastic deformation occurs. In the elastic region, Hooke's Law gives the relationship between the load and the extension:

$$\delta = Pl/AE$$

Where P = applied stress, l = original length of specimen, A = cross sectional area, δ = total extension of the specimen and E = modulus. As shown in the above equation, the applied load and the length of the specimen is directly proportional to the extension of the specimen. The tensile stress can be calculated as $\sigma = P/A$, where σ is applied stress (Pa) and the tensile strain can be determined by $\varepsilon = l/l_o$. Hence, Young's modulus is calculated as $E = \sigma/\varepsilon$.

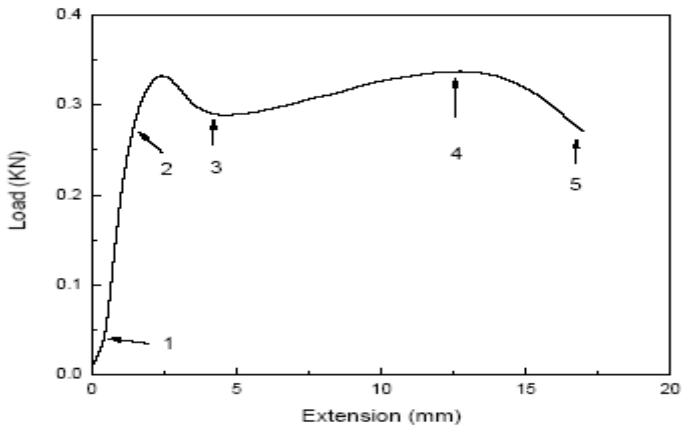


Figure 2.20 Load-extension curve [6]

Figure 2.20 illustrates a typical load-extension curve. The area under the curve between points 1 and 2 is called the elastic region where the material will return to its original shape when the load is removed. After the point 2, yield point, the area between points 2 and 5 is the plastic region where the sample undergoes a permanent shape change. The point 4 is the ultimate tensile strength and the point 5 is where sample fractures.

2.8.2 Impact Analysis

For impact testing, either Charpy or Izod test machines can be used. Impact resistance of a composite material varies with the volume fraction of fibres and its orientation within the material. Composites tend to have higher toughness with shorter and thicker fibres.

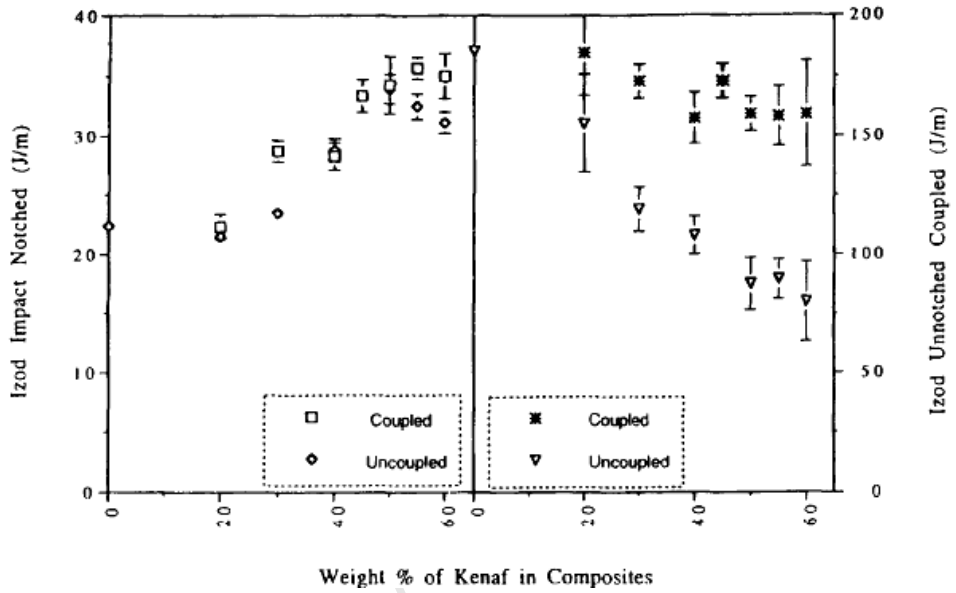


Figure 2.21 Effect of amount of kenaf fibre on the impact strength of the kenaf / PP composites [35]

The impact strength of a composite depends on the amount of fibres and the types of testing samples, notched or un-notched. With the notched samples, an addition of fibres increases the impact strength. On the other hand, the impact strength of the un-notched sample decreased with addition of fibres. In case of the notched samples, the fibre bridges are cracked due to the impact stresses and this increases the resistance of propagation of the crack [35]. In case of the un-notched samples, addition of the fibres created a stress concentration region and this accelerated the crack initiation [35]. It was found that a flexible interface increases the resistance to crack initiation.

2.8.3 Three Point Bending Analysis (Flexural Testing)

Through the three point bending test, the flexural modulus, flexural stress (σ_f), flexural strain (ε_f) and the flexural stress-strain response of the material can be determined. The main advantage of a three point bend test is the ease of specimen preparation and testing.

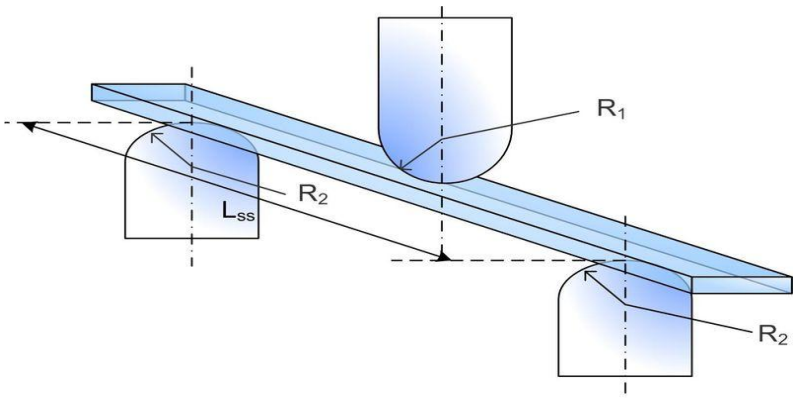


Figure 2.22 Schematic illustration of the three point bend tester

The flexural stress, flexural strain and Young's modulus can be calculated by utilising the following equations.

- Flexural stress

$$\sigma_f = \frac{3PL}{2bd^2}$$

- Flexural strain

$$\epsilon_f = \frac{6Dd}{L^2}$$

- Young's modulus

$$E_B = \frac{L^3 m}{4bd^3}$$

σ_f - Stress at midpoint (MPa)

ε_f - Strain (%)

E_B -Modulus of elasticity

P - Load (N)

L - Support span (mm)

B - Width (mm)

D - Thickness (mm)

D - Maximum deflection of the centre (mm)

M - Slop of the tangent of the load deflection curve (N/mm)

2.8.4 Differential Scanning Calorimetry Analysis (DSC)

Differential scanning calorimetry (DSC) is one of the most widely used thermo-analytical techniques to characterise the thermal transition properties of materials. Both reference and sample pans are heated at the same rate. In order to keep the temperature increasing for both pans at the same rate, the sample pan with the polymer requires more heat than that of the reference pan. The DSC measures exactly how much more heat has to be put out to balance the difference in the amount of heat required to increase the temperature of a sample and a reference pan.

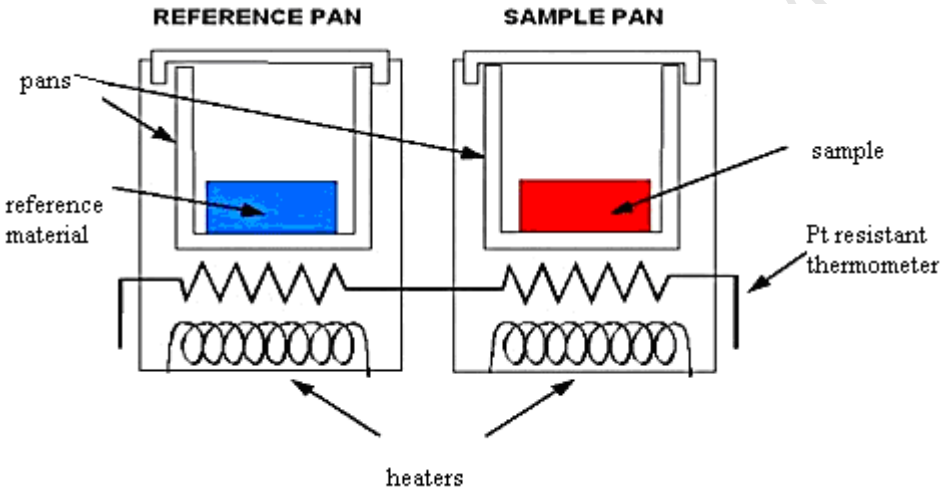


Figure 2.23 Schematic illustration of DSC tester

Using the DSC technique, it is possible to observe the following thermal properties of materials.

Table 2.13 DSC measurement and its purpose [6]

Glass transition temperature (Tg)	Oxidative stability
Crystallisation temperature (Tc)	Specific heat measurement
Melting point (Tm)	Purity measurement
Kinetics	Quality control of raw materials

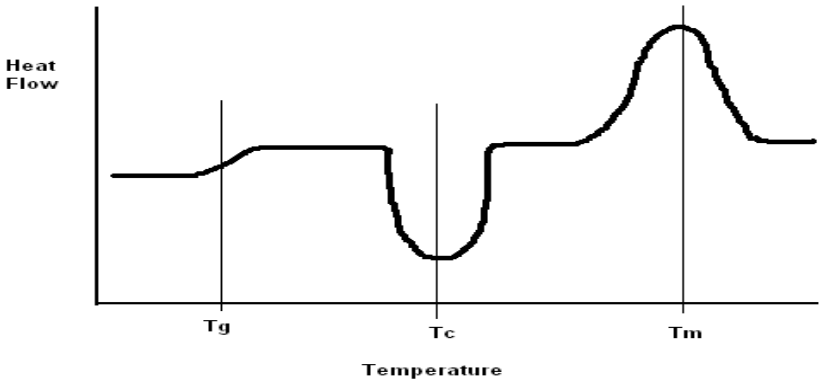


Figure 2.24 Schematic illustration of thermal transitions

- **Glass transition temperature (Tg)**

The amount of heat required to increase the temperature of material is called heat capacity (Cp). Polymers have a higher heat capacity above the Tg. The glass transition temperature point shows on the DSC plot as a sudden upward shift.

- **Crystallisation temperature (Tc)**

Above the Tg, polymer chains have high mobility. When the right temperature is reached, polymer molecules gain enough energy to move into very ordered arrangements, called crystals. When polymer molecules fall into the crystalline arrangements, they give off heat (exothermic transition) which shows as the lowest dip on the DSC plot.

- **Melting temperature (Tm)**

If heat is added over and beyond the Tc, the polymer crystals will begin to melt and move around freely. In order to melt, polymer crystals must absorb heat, which results in endothermic transition as shown on the graph in figure 2.24 above.

- **Degree of crystallinity (Xc)**

DSC can indicate how much polymer is crystalline or amorphous. The degree of crystallinity can be calculated by utilising the following equation:

$$X_C = \frac{\Delta H_f}{\Delta H_f^o} \times 100$$

ΔH_f = heat of fusion, ΔH_f^o = heat of fusion of a 100% crystalline isotactic material

2.8.5 Failure Mechanism Analysis

In order to understand the failure mechanism of a natural fibre reinforced polymer composites, it is important to understand the interfacial bonding between ultimate cells and orientation variations of micro-fibrils in each cell due to the structural characteristics of the fibres [43]. The fibre reinforced polymer composites are heterogeneous and the individual laminates are structured in an anisotropic way. Internal material can be observed in the damaged zone, generally in the fibre-matrix interfacial region. The material failure shows as fibre breakage, fibre separation (debonding), delamination and matrix micro-cracking [36]. Unlike glass and carbon fibres, natural fibres consist of bundle of filaments. As shown in the figure 2.25, natural fibre consists of rigid cellulose micro-fibrils which are embedded in a lignin and hemi-cellulose matrix. These micro-fibrils are helically wound along the fibre axis to form ultimate hollow cells [43]. These helically arranged crystalline micro-fibrils are uncoiled under stress. This is one of the predominant failure modes since it consumes large amounts of energy.

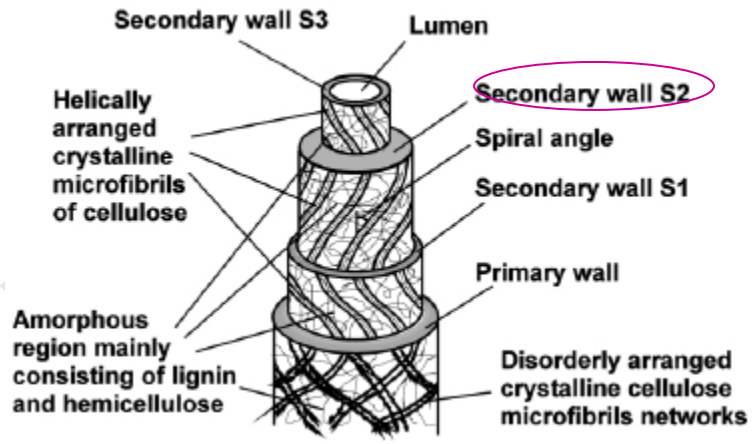


Figure 2.25 Illustration of natural fibre cell; the secondary wall S2 is the main load bearing component [43]

2.8.6.1 Effect of fibre treatment on failure mode

The effect of fibre treatment on the mechanical properties of sisal fibre reinforced epoxy composite was studied by Rong et al [43]. In their research, sisal fibre surface and its internal structures were modified by alkalisation.

Untreated sisal fibre reinforced epoxy laminates failed due to decohesion of cells by cell pull out as represented in the figure 2.26. A weaker interfacial bonding strength resulted in stretching and uncoiling of micro-fibrils in the cells which decreased the mechanical performance of composites.

The alkalisation process removes the hemi-cellulose and the lignin and as a result, it leaves the vacancies in sisal bundles. Removal of cementing material by the alkali treatment allows penetration of epoxy which resulted in a better interfacial bonding between the fibre bundles and the matrix.

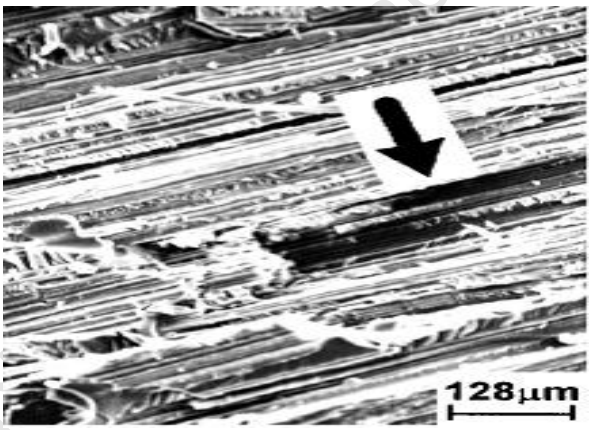


Figure 2.26 SEM micrographs of fractured surface of sisal/epoxy composites due to tension; arrow indicates the cell pull out [43]

2.8.6.2 Effect of fibre content on failure mode

The effect of fibre content on the failure mode of glass fibre reinforced epoxy laminates was studied by Okoli et al [36]. Figure 2.27 presents the SEM micrograph of the fracture surface of 15.5% fibre reinforced epoxy composites. The broken fibre end indicates a brittle fracture and river marks shows the direction of crack propagation in the matrix. The smooth fibre surface suggests poor fibre-matrix adhesion which resulted in delamination. Delamination of the matrix indicates the occurrence of matrix shear failure [36].

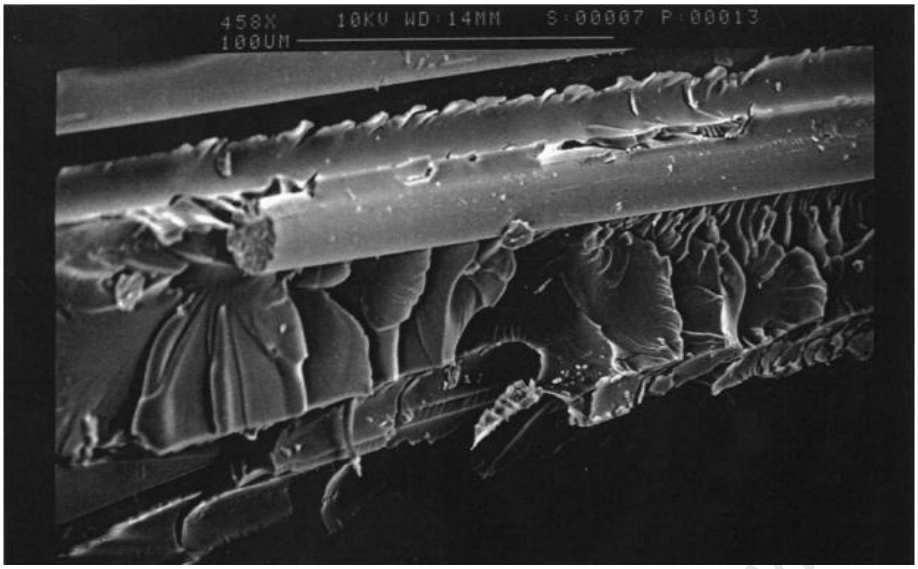


Figure 2.27 Glass/Epoxy laminates with 15.5% fibre volume fraction

It was reported that the composite with high fibre volume fractions, such as 40-50%, composite commonly exhibits a brittle failure with fibre pullout [55]. As shown in figure 2.28, as the fibre volume fraction increases to 41.2%, the SEM micrograph shows bunch fibre pullout with little matrix adhesion.

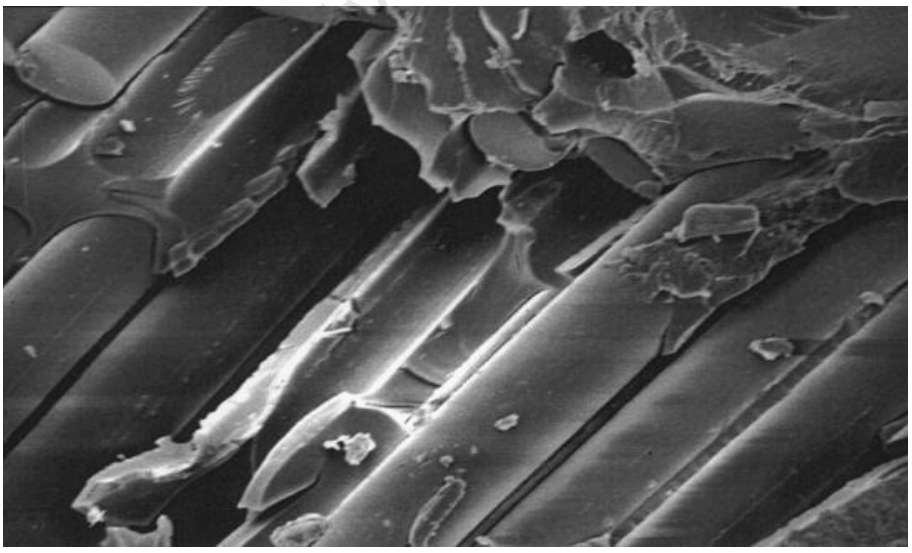


Figure 2.28 Glass/Epoxy laminates with 41.2% volume fraction

2.8.6.3 Effect of strain rate on failure mode

Increasing strain rate results in increasing failure energy absorption. This is due to the higher energy requirement of the matrix to sustain fracture as test the speed increases. In consequence, with increase in strain rate, the energy involved in the failure of composites can be also seen from the increase in the area under the stress-strain curve [36].

Figure 2.29 shows the tensile fracture surface of Tufnol (glass/epoxy) laminate tested under the strain rate of 1.7×10^{-2} mm/s. The fracture surface clearly shows a rough fibre fracture surface and the fibre end indicate a brittle failure mode. However, there are signs of fibre-matrix adhesion at the interphase region which leads to brittle failure since interfacial bonding influences the inter-laminar shear strength and the inter-laminar tensile strength [56].

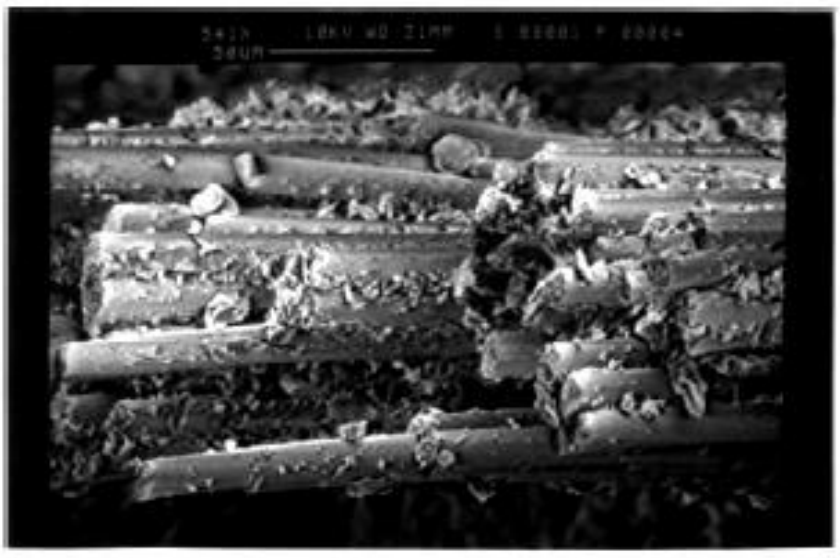


Figure 2.29 Tufnol 10G/40 laminate tested at 0.017 mm/s [57]

Figure 2.30 shows the tensile fracture surface of Tufnol laminate tested at a test speed of 10 mm/s. The SEM result shows fibre bunches pulled out with signs of fibre-matrix adhesion. As the testing speed increases, the damage in matrix increases against the interfacial bond strength. This bunch fibre pull out implies that at this loading rate, the fibre-matrix interfacial bond strength was greater than the tensile failure strength of the composites [36].

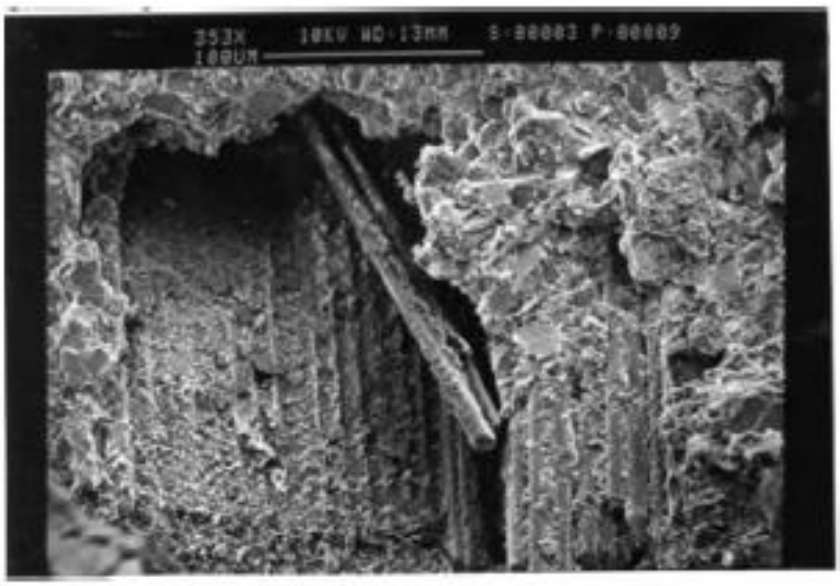


Figure 2.30 Tufnol 10G/40 laminate tested at 10 mm/s [57]

Figure 2.31 shows a magnified view of the tensile fracture surface of the Tufnol laminate tested at 2000 mm/s. The SEM result clearly shows the matrix debonding due to fibre pull out. Debonding resulted in cracking and disintegration of the matrix.

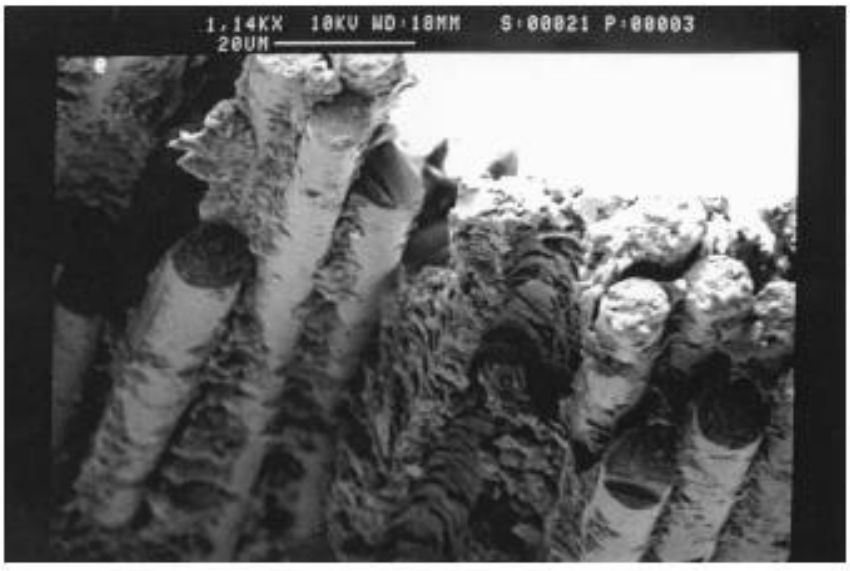


Figure 2.31 Tufnol 10G/40 laminate tested at 2000 mm/s [57]

CHAPTER THREE

EXPERIMENTAL TECHNIQUES

This chapter gives all the experimental methods used in this research work. The compounding and moulding process of the kenaf fibre reinforced polypropylene composites are described in detail. The injection and compression moulded tensile test specimens were prepared and then subjected to thermal, mechanical and microscopic analysis. The tensile test specimens were prepared by following the ISO (International Standard Organisation) standards. The SEM (scanning electron microscope) was also used to observe the microstructural changes observed on the impact failure surfaces.

3.1 MATERIALS TESTED

3.1.1 Raw Materials

In this research, both international and local kenaf bast fibres were tested. Fibres were approximately 5cm in length. The international (from Bangladesh) and the local (from Winterton in KwaZulu Natal) kenaf bast fibres were supplied by Sustainable Fibre Solutions (Pty) Ltd. The chemical and physical compositions of the kenaf fibres are presented in the table 3.1.

Table 3.1 Kenaf data sheet [Sustainable Fibre Solutions (Pty) Ltd]

Chemical/ Physical Data	
Chemical Composition:	
Cellulose (wt. %)	61 – 71.5
Hemicellulose (wt. %)	13.6 – 20.4
Lignin (wt. %)	12 – 13
Pectin (wt. %)	0.2
Wax (wt. %)	0.5
Moisture Content (wt. %)	12.6 – 16
Physical Composition:	
Density g/cm^3	0.013 – 0.0155
pH	Neutral
Appearance/Odour	Light brown to gray/mild odour.

Two different sizes of kenaf milled core were supplied by the Drotsky Hammer mill manufacturer; 60 mesh core powder and 35 mesh kenaf core grains were supplied. Cores were produced through a 500 micron and 0.6mm screen. The polypropylene was supplied by Sasol (Pty) Ltd.

Figure 3.1 Kenaf fibres (a) International kenaf bast fibre (b) Local kenaf bast fibre (c) Kenaf core powder (60 mesh) (d) Kenaf core grains (35 mesh)

3.1.2 Compatibiliser

The compatibiliser Maleic Anhydride Grafted Polypropylene (MAPP), known as Optim P-403 was used for studying the adhesion between the PP matrix and the kenaf fibres. The physical and chemical properties of the Optim P-403 compatibiliser are listed below:

- Form: pellets
- Appearance/ Odour: free flowing pellets, white to pale yellow in colour, with slight odour and taste
- Boiling point (MA): 100°C
- Solubility in water: insoluble

3.2 PROCESSING OF KENAF/ PP COMPOSITES

To determine the effect of fibre content on thermal and mechanical properties of the kenaf fibre reinforced polypropylene composites, various percentages of the kenaf fibres (weight %) were added to the polypropylene matrix. 2% MAPP modified polypropylene matrix was prepared prior to compounding with the kenaf fibres. The loading of kenaf fibres were varied between 20 to 40% total weight of the composites. Generally, when the composite contains more than 30% fibre content, it experiences a very low permeability the barrel of the extruder and injections moulder. Due to this reason, previously compounded samples were subjected to compression moulding instead of the injection moulding. The balance of the mixture was made up with the polypropylene granules which give a total weight of 100% per batch size.

To study the effects of coupling agents, different percentages (weight %) of MAPP coupling agent were added to the kenaf fibre reinforced polypropylene composites. Loading of the MAPP coupling agent varied from 2 to 5%. The fibre content was kept constant at 30% to total weight of the composites. The balance of the mixture was made up with the polypropylene granules to give a total weight of 100%. Then the mixture was formed into the tensile specimens by using an injection moulder.

Additionally, the effects of moulding process on the mechanical and the thermal properties of eco-composites were investigated. For this purpose, the tensile test specimens which contain the exact same composition of fibres and matrix were prepared. These specimens were formed by injection moulding and compression moulding. In both cases, 20% and 30% kenaf fibres were incorporated into the MAPP modified polypropylene matrix. During the moulding process, the test specimen specification and the moulding conditions were kept the same.

Furthermore, the potential usage of the kenaf core fibre as a filler material and its effect on adhesion between the matrix and the fibres were also investigated. Different sizes of core such as 35mesh core powder and 60mesh core grains were investigated.

Total filler content (30 wt %) and MAPP content (4 wt %) were kept constant. The composition of the kenaf core fibre filled PP composites are summarised in the table 3.2. Tensile, flexural and impact tests were performed to determine the potential usage of kenaf core fibre filled polypropylene composites.

Table 3.2 Composition of kenaf bast / core fibre filled PP composites (in weight %)

	Bast Fibre	Core Fibre	PP	MAPP
Kenaf bast fibre Composites	10	0	86	4
	20	0	76	4
	30	0	66	4
Kenaf bast-core hybrid composites	10	20	66	4
	20	10	66	4
	30	0	66	4
Kenaf core Composites	0	10	86	4
	0	20	76	4
	0	30	66	4
PP	0	0	96	4
Kenaf bast-core composites with increased MAPP	0	30	64	6
	20	10	64	6

Finally, local kenaf fibre reinforced PP/MAPP composites were prepared to compare the properties with that of international kenaf fibre reinforced composites. 30% (wt %) kenaf fibres were used. The local kenaf fibre reinforced composite specimens were moulded in exactly the same way as that of the international kenaf fibre reinforced composites.

3.2.1 Drying

Since the kenaf fibre has a high tendency of absorbing moisture from the atmosphere, it is important to dry them before compounding. The kenaf fibres were dried in a dehumidifier at 60°C overnight.

3.2.2 Extrusion (Mixing and Compounding)

Polypropylene granules were pre-mixed with varying percentages of MAPP (2 to 5%). PP/MAPP mixed granules were compounded in a single screw extruder (Rapra, L/D 25). Due to the low permeability of kenaf fibres, the mixture was manually fed into the feeding zone. The screw speed was varied between 25 and 30 rpm. The temperature used during the mixing and compounding process was kept lower than 200°C to avoid thermal degradation of kenaf fibres. The applied temperatures in the different zones of the extruder are shown in the figure 3.2. The thin strands of PP/MAPP compounds were pelletised using a side cut pelletiser and stored for the fabrication process. The resultant cylindrical pellets had an approximate length of 4 mm.

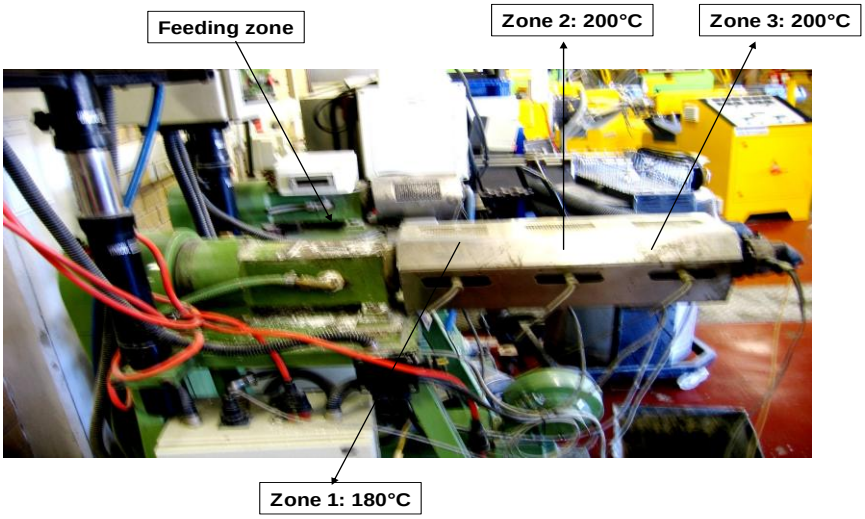


Figure 3.2 Temperature zones of extruder [CSIR, Pretoria]

3.2.3. Composite Fabrication

Figure 3.3 presents the process which was employed for fabricating the kenaf fibre reinforced PP composites. The compounded PP/MAPP pellets were converted into thin sheets by compression moulding. Pellets were compressed at 190^{o}C for 4 minutes under constant pressure of 5 tons. Then the varying percentages of kenaf fibres (20 to 40 wt %) and the milled kenaf core (0 to 30 wt %) were added to the PP/MAPP sheets in a sandwich form. The different compositions of each composite material were explained in the beginning of this chapter. Then, the sandwiched composites were compression moulded again at 190^{o}C for 8 minutes. For injection moulding, it is preferable to have fibre lengths shorter than 1 cm. For this reason, sandwiched composites were granulated and resulted in a short length of kenaf fibre composites. Finally short composite granules were extruded again (mixing) and chopped (granulation) prior to the injection and the compression moulding processes.

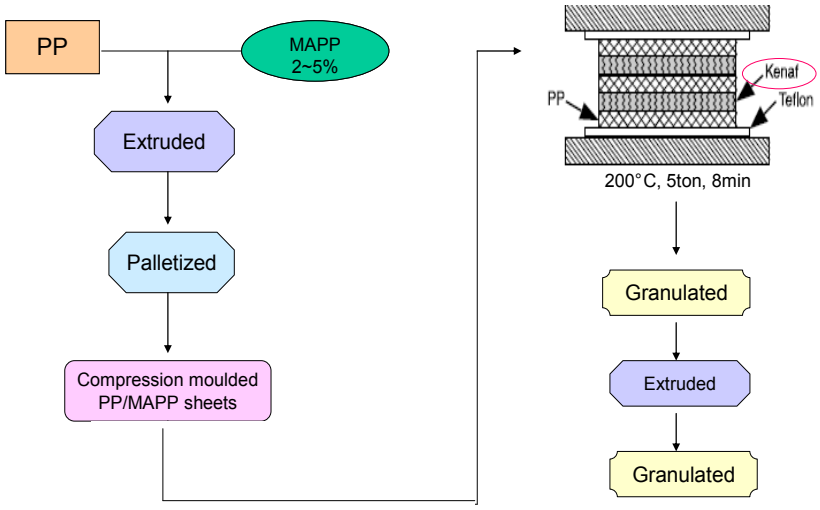


Figure 3.3 A schematic illustration of the kenaf/PP fabrication process

3.2.4 Moulding

The tensile test specimens were prepared by injection and compression moulding. The test specimens were formed under the standard operating conditions by following the International Standard Organisation (ISO) standard.

3.2.4.1 Injection Moulding

The applied injection moulding (Engel Injection Moulder) conditions were as follows: The temperatures barrels 1 to 3 were 200^{o}C, 210^{o}C and 220^{o}C. The tensile test specimens were moulded using an injection speed of 5 mm/s and at an injection pressure of 120 bars. The melting temperature at the nozzle was 230^{o}C and the moulding temperature was kept constant at room temperature while the cooling time was set for 20 seconds. Due to the low permeability of natural fibres, kenaf fibres were force fed into the feeding zone. Dog-bone shaped tensile test specimens were moulded by following the ISO standards. Prior to testing, the specimens were left for at least 12 hours in the dehumidifying drier at 60^{o}C to remove any moisture. Figure 3.4 shows the injection moulder which was used for this research work.

Figure 3.4 Engel injection moulder [CSIR, Pretoria]

3.2.4.2 Compression Moulding

Following the extrusion process, dried kenaf fibres with the desired weight % were added to the PP/MAPP compressed sheets. The mixture was placed in an open picture frame mould. The thickness of the frame was 4 mm. Then the frame was placed under the compression moulder (Pasadena Hydraulics Inc) at a temperature of 190ºC. During the first 5 minutes of the compression moulding process, the materials were kept at constant pressure of 5 tons and then held at a pressure of 12 tons for further 3 minutes. This was followed by cooling under the 5 tons pressure. After compression moulding, the fabricated eco-composites were then cut into the dog-bone shaped tensile specimens by following the ISO standards. Prior to testing, the specimens were left for at least 12 hours in the dehumidifying drier at 60^{o}C. Figure 3.5 shows the compression moulder which was used for this research work.

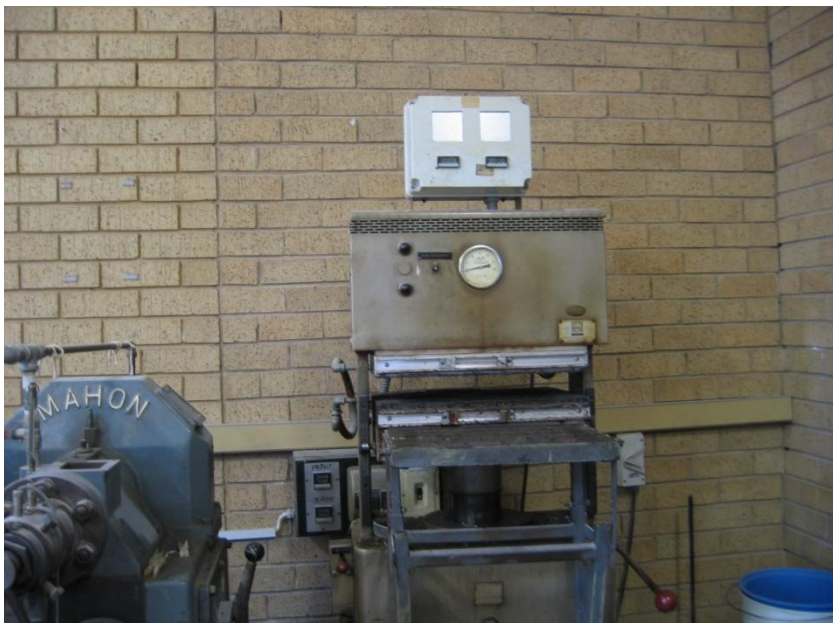


Figure 3.5 Compression moulder [CISR, Pretoria]

3.3 MECHANICAL ANALYSIS

The mechanical properties of the kenaf fibre reinforced polypropylene composites were determined at room temperature. The kenaf bast fibre and kenaf core fibre filled polypropylene test samples were subjected to tensile, flexural and Charpy impact testing. The tensile testing was conducted at the Centre for Materials Engineering, University of Cape Town, while the flexural test and the impact test were conducted at Plastamid (Pty) Ltd in Cape Town. The ISO standards were followed for conducting all the mechanical tests.

3.3.1 Tensile Testing

Tensile tests were conducted on both the injection moulded and the compression moulded specimens. The tensile test specimens were pulled in tension on the Zwick 1484 Universal Tensile Tester under the strain rate of 5 mm/min. The tensile tests were carried out according to ISO R527. Test specimens had a gauge length of 80 mm, a thickness of 4 mm and a width of 10 mm. The tensile strength of the composites was determined from the maximum load reached after the initial elastic portion of the curve. In most cases, the Young's modulus could not be determined as the material displayed plastic flow from the beginning of loading. The elongation to failure was obtained from the tensile stress-strain graph. Additionally, to study the effect of testing speed on the tensile properties of kenaf fibre reinforced PP composites, different strain rates were applied. These applied test speeds were 0.25, 5, 100 and 200 mm/min.

Figure 3.6 Zwick 1484 Universal tensile test machine

3.3.2 Impact Testing

The notched Charpy impact tests were performed on the kenaf fibre reinforced polypropylene composites. Impact tests were performed with the Zwick/ Roell 5113.1 impact tester according to ISO180. The specifications of test specimen were width of 10 mm, length of 80 mm and thickness of 4 mm. The notch radius was 2mm. Test specimens were tested with the 4.0 J ENT hammer size at the release angle of 160 degrees. Five impact test specimens were tested for each batch of sample. The impact resistance was recorded in kJ/m^2. The impact test machine is shown in the figure 3.7(a).

3.3.3 Three Point Bend Testing

The three point bend test was carried out according to ISO178. The LLOYD Instrument LC 2.5 kN tester was used to measure the flexural strength of the composites as shown in figure 3.7(b). The dimensions of test specimen were: width of 10 mm, length of 80 mm and thickness of 4 mm. The supporting span length was 60 mm and a test speed of 5 mm/min was employed.

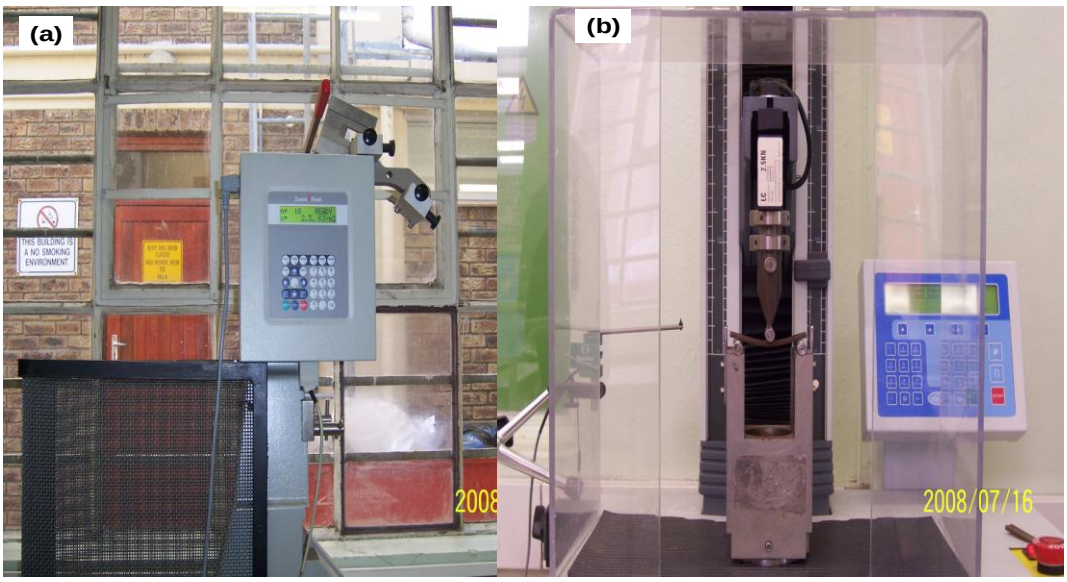


Figure 3.7 (a) Zwick/ Roell 5113.1 impact tester (b) LLOYD Instrument LC 2.5 kN 3 point bend tester

3.4 THERMAL ANALYSIS

3.4.1 Differential Scanning Calorimetry (DSC)

The thermal properties of the kenaf / PP composites were measured by using a DSC Q100 differential scanning calorimeter coupled with a data station. Samples of about 3 mg were heated from 60 to 200ºC at a heating rate of 10ºC / min and held for 1 minute in order to eliminate the previous thermal history. The sample was then cooled at a rate of 10ºC / min to 60ºC to recrystallise the sample and measure the crystallisation temperature. After cooling, the sample was reheated from 60ºC to 200 ºC to measure the melting temperature and heat of fusion. The values of crystallisation temperature (Tc), melting temperature (Tm) and heat of fusion (ΔH_f) could be obtained from the DSC graph. In order to calculate the percentage crystallinity, the known heat of fusion of a 100% crystalline isotactic polypropylene which is assumed to be 209.3 J/g [51] was used. The percentage of crystallinity (Xc) of the different composites was then calculated utilising the following equation:

$$\textbf{\% crystallinity (Xc)} = \frac{\Delta H_f}{\Delta H_f^o} \times 100 = \frac{\Delta H_f}{209.3 J/g} \times 100$$

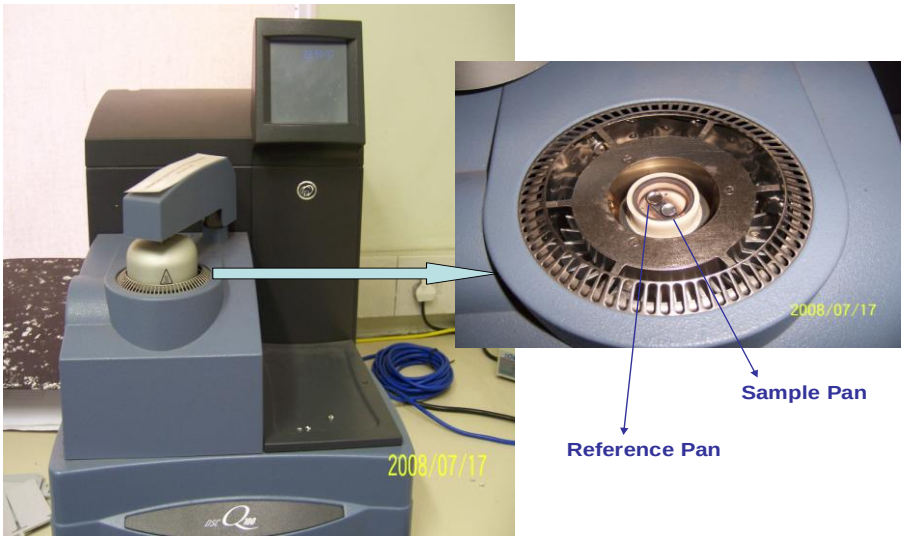


Figure 3.8 DSC Q100 differential scanning calorimeter

3.5 MORPHOLOGICAL ANALYSIS

3.5.1 Scanning Electron Microscopy (SEM)

In order to correlate the effects of applied mechanical and thermal stresses on the specimens and its effect on microstructural changes, a LEO Stereo-scan 440 Scanning Electron Microscope (SEM) was used. The fractured impact specimens were cut into random sizes and placed on the aluminium stubs using electron conductive glue. The samples were then sputter coated with gold and palladium mixture before being examined in the SEM. The SEM micrographs of impact fractured samples were taken at 10 kV. Different parts of the fracture surface of the samples were analysed to examine the adhesion between kenaf fibres and the polypropylene matrix and to identify the failure mechanism of the kenaf fibre reinforced polypropylene composites.

Figure 3.9 LEO Stereoscan 440 Scanning Electron Microscope (SEM)

CHAPTER FOUR

EXPERIMENTAL RESULTS

4.1 INTRODUCTION

This chapter presents various tests results obtained from the mechanical, thermal and morphological analysis performed on the kenaf fibre reinforced polypropylene composites. The effects of fibre loadings, MAPP compatibiliser contents, addition of kenaf core, different testing speeds and different moulding procedures on the test specimens were investigated. Additionally, the properties of the local kenaf fibre reinforced composites were compared to that of the international kenaf fibre reinforced composites. This chapter is divided into the following sections:

- Mechanical properties of the fibre composites
- Thermal properties of the fibre composites
- Morphological properties of the fibre composites

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4.2 MECHANICAL PROPERTIES OF THE COMPOSITES

4.2.1 Effect of Fibre Content on Tensile Properties

Figure 4.1 and table 4.1 show the effects of increasing fibre content on the tensile properties. Kenaf fibres were added to a 2% MAPP coupled polypropylene matrix. The tensile strengths of the kenaf fibre reinforced PP composites increased from 29 MPa to 35.2 MPa with increasing fibre content from 0 to 30 wt %. However, when 40 wt % of kenaf fibre was added, a significant decrease in tensile strength was observed. In all cases, as the tensile strength increased, there were substantial decreases in failure strains.

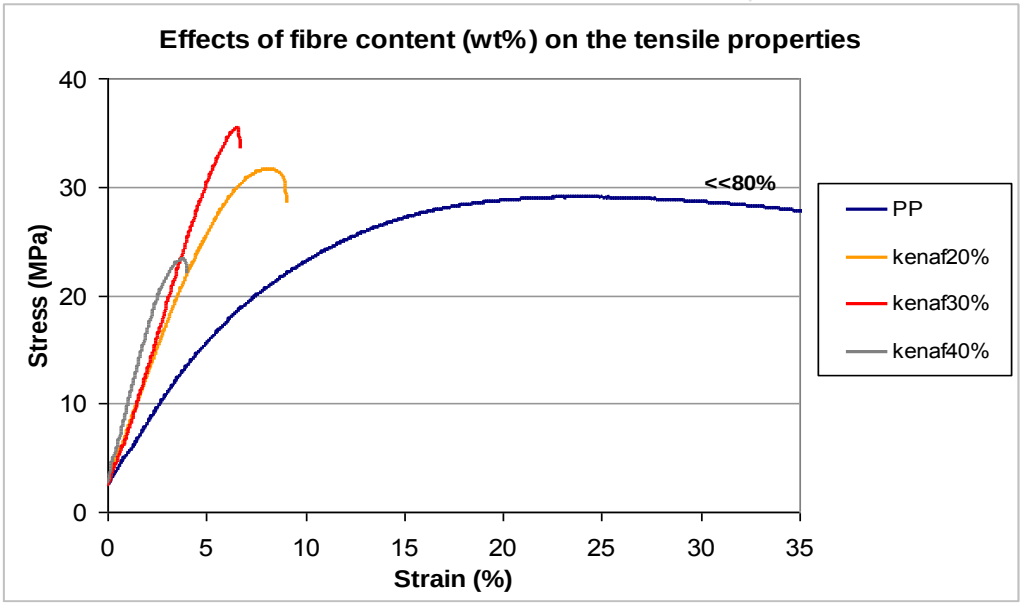

Figure 4.1 Effects of fibre content on tensile strength

Table 4.1 Effects of fibre content on tensile strength and failure strain

Fibre Content (wt %)	Average Tensile Strength (MPa)	Strain at Break (%)
0	30.1 ± 0.25	<<80 ± 19.8
20	31.6 ± 0.58	9.1 ± 0.25
30	35.2 ± 0.05	6.7 ± 0.27
40	23.3 ± 0.37	4.0 ± 0.27

4.2.2 Effect of Fibre Content on Flexural Properties

It can be seen from figure 4.2 that the flexural strength and flexural modulus increased with increasing fibre content. Although increasing the fibre content resulted in a marginal increase in the flexural strength (49.8 MPa to 60 MPa), a significant increase in the flexural modulus was observed as the fibre content increased from 0 to 40%. The flexural modulus increased from 1.6 GPa to 4.5 GPa as the fibre content increased from 0 to 40%. The 40% kenaf fibre content showed the highest value of flexural strength and flexural modulus. Table 4.2 summarises the effect of increasing fibre content on the flexural properties of the kenaf fibre reinforced PP composites.

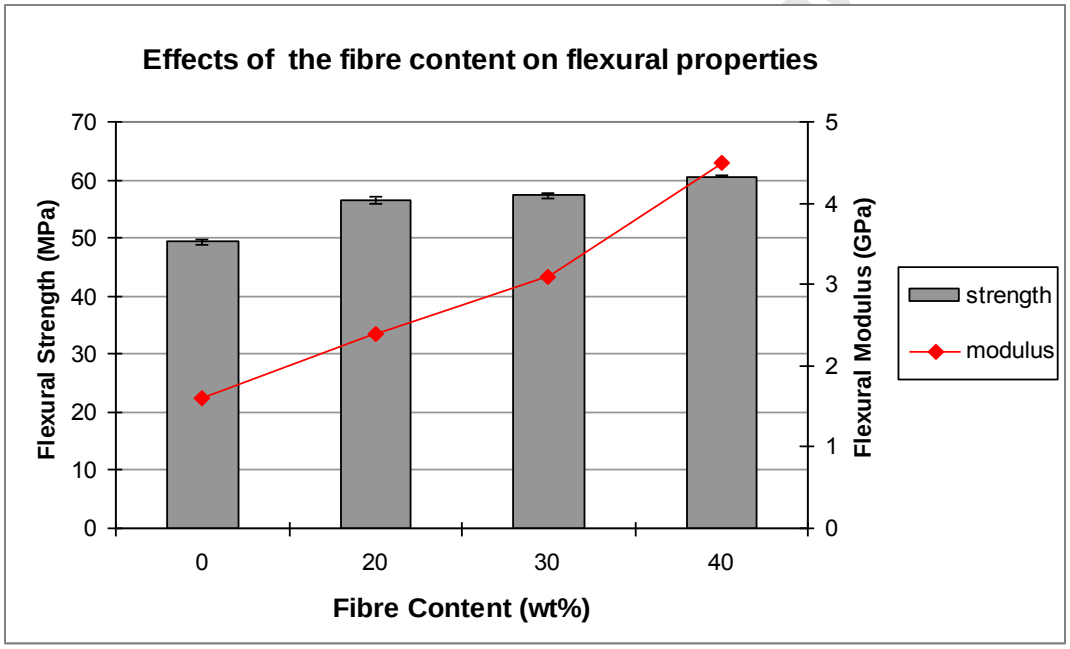

Figure 4.2 Effects of fibre content on flexural strength and modulus

Table 4.2 Effect of fibre content on flexural strength and modulus

Kenaf Fibre Content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0	49.3 ± 0.51	1.6 ± 0.47
20	56.5 ± 0.73	2.4 ± 0.22
30	57.3 ± 0.55	3.1 ± 0.28
40	60.6 ± 0.24	4.5 ± 0.19

4.2.3. Effect of Fibre Content on Impact Resistance

Figure 4.3 shows the effect of fibre content on the impact resistance of compression moulded kenaf fibre reinforced PP composites. It was observed that increasing the fibre content resulted in a marginal decrease in impact resistance. As the fibre content increased from 0 to 30%, the impact resistance decreased from 4.38 kJ/m² to 3.95 kJ/m². The error bars indicate one standard deviation.

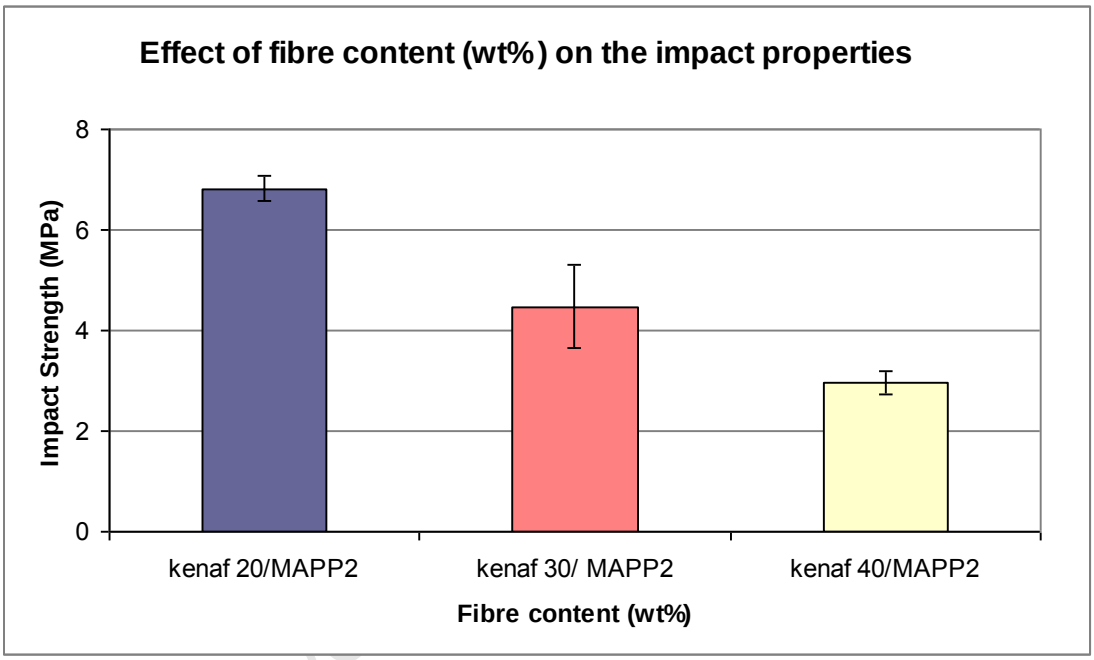

Figure 4.3 Effect of fibre content on impact resistance

Table 4.3 Effects of increasing fibre content on impact resistance

Fibre Content (wt %)	Impact Resistance (kJ/m²)
20	6.8 ± 0.14
30	4.5 ± 0.26
40	2.9 ± 0.81

4.2.4 Effect of MAPP Content on Tensile Properties

The results indicate that increasing the coupling agent (MAPP) content resulted in a significant increase in tensile strength of the kenaf fibre reinforced PP composites (See figure 4.4 and table 4.4). As the MAPP content increased from 2 to 4 (wt %), the tensile strength increased from 31.6 MPa to 40.4 MPa. The tensile strength increased by about 28%. When the fibres were modified with 4% MAPP content, the composite reached its maximum tensile strength, but it decreased to 35.1 MPa as the MAPP content increased to 5%. Hence, 4% is the optimum coupling agent content for the kenaf fibre reinforced PP composites. In all the cases, a substantial decrease in failure strain was observed with increasing MAPP content.

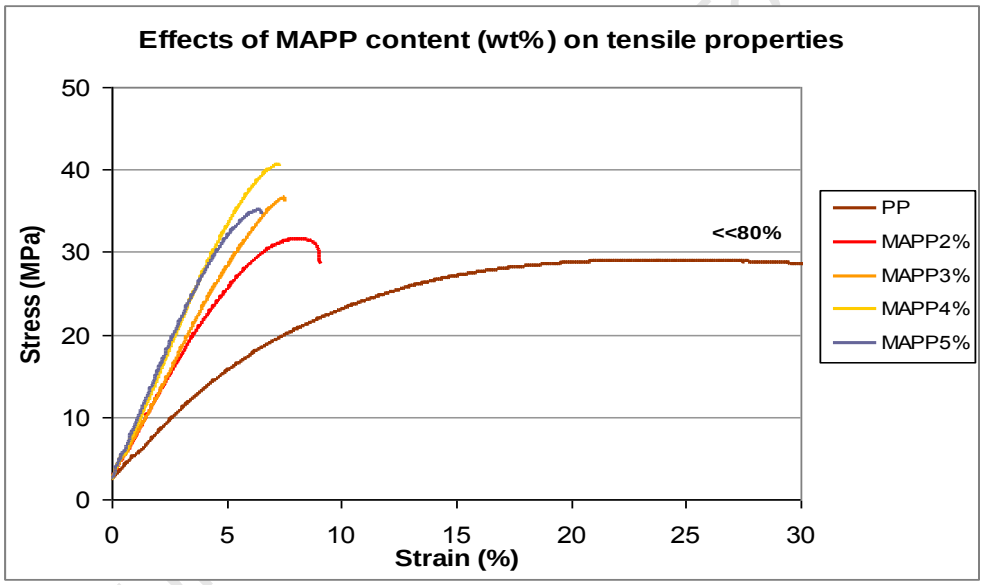

Figure 4.4 Effects of MAPP content on tensile properties

Table 4.4 Effect of MAPP content on tensile strength and failure strain

MAPP Content (wt %)	Average Tensile Strength (MPa)	Stress at Break (%)
0(PP)	30.1 ± 0.25	<<80 ± 19.24
2	31.6 ± 0.31	9.1 ± 0.43
3	36.5 ± 0.22	7.6 ± 0.36
4	40.4 ± 0.42	4.0 ± 0.93
5	35.1 ± 0.53	3.5 ± 0.41

4.2.5 Effect of MAPP Content on Flexural Properties

Figure 4.5 shows the results of flexural strength and flexural modulus of the kenaf fibre reinforced PP composites with respect to increasing the amount of MAPP coupling agent. The flexural strength and flexural modulus increased as MAPP content increases from 2 to 4 wt %. The kenaf fibre reinforced PP composite coupled with the 4% MAPP showed a maximum value of flexural strength and flexural modulus (67 MPa and 4.4 GPa). A further increase in MAPP content to 5%, however, resulted in a decrease in both flexural strength and modulus. These values are summarised in the table 4.5.

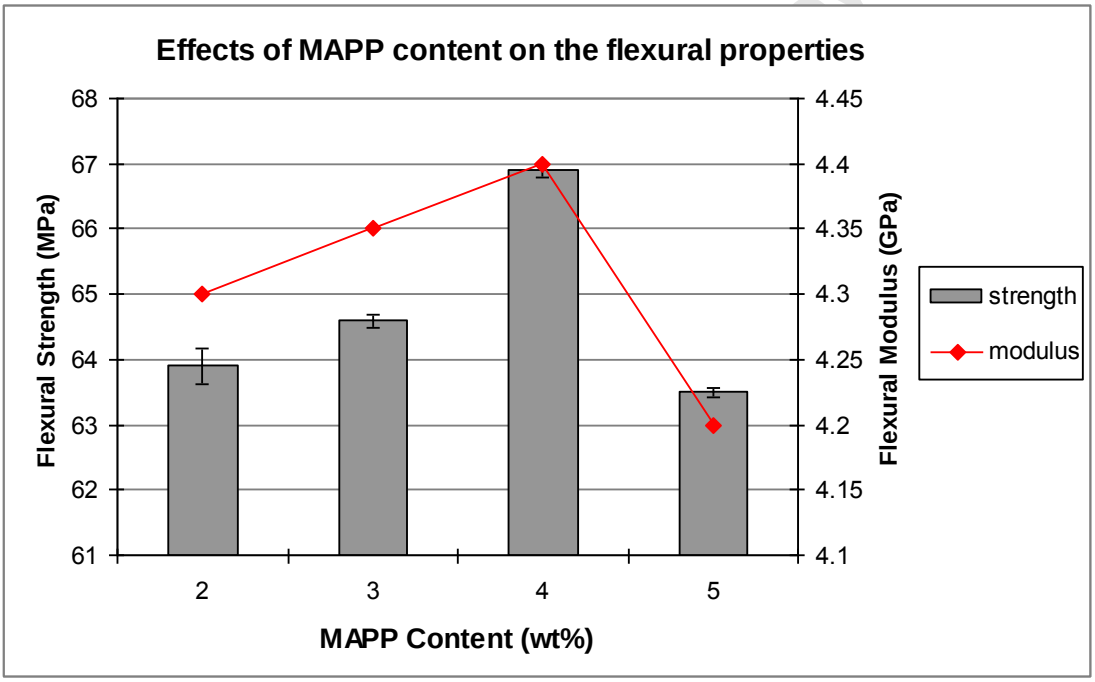

Figure 4.5 Effects of MAPP content on the flexural properties

Table 4.5 Effects of MAPP content on flexural strength and flexural modulus

MAPP content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
2	63.9 ± 0.28	4.3 ± 0.25
3	64.6 ± 0.13	4.3 ± 0.09
4	66.9 ± 0.13	4.4 ± 0.09
5	63.5 ± 0.07	4.2 ± 0.05

4.2.6 Effect of MAPP Content on Impact Resistance

Figure 4.6 presents the effects of increasing MAPP content on the impact resistance of injection moulded kenaf fibre reinforced PP composites. As the coupling agent content increased from 2 to 4 (wt %), the impact resistance decreased from 3.95 kJ/m² to 3.91 kJ/m². By considering the scatter on the measured values of the impact resistance of 2% to 4% coupled composite, it was difficult to say increasing MAPP content had a significant effect on the impact resistance. However, a significant increase in impact resistance was observed at 5% MAPP content. The measured impact resistance are summarised in the table 4.6.

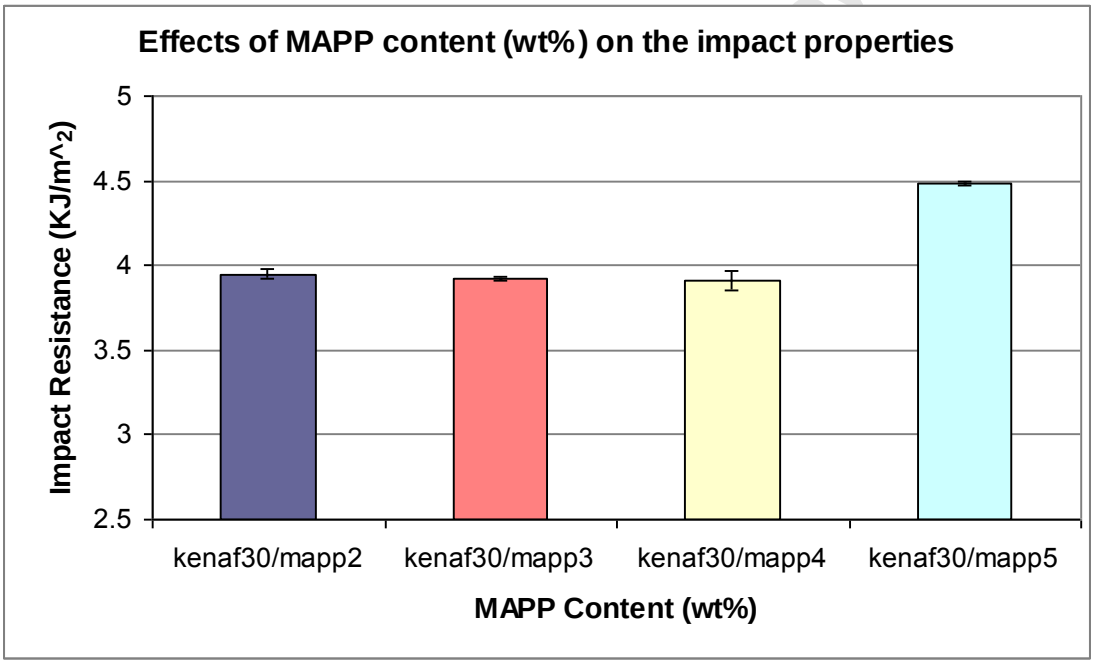

Figure 4.6 Effect of MAPP content on impact resistance

Table 4.6 Effect of MAPP content on the impact resistance

MAPP Content (wt %)	Impact Resistance (kJ/m²)
2	3.95 ± 0.03
3	3.92 ± 0.01
4	3.91 ± 0.06
5	4.49 ± 0.01

4.2.7 Effect of Moulding Process on Flexural Properties

Table 4.7 presents the effects of different moulding processes on the flexural properties of kenaf fibre reinforced PP composites. Tensile test specimens with exact specifications were produced by injection and compression moulding processes. During moulding, 2% MAPP modified kenaf fibres were incorporated into the polypropylene matrix. The kenaf fibres were varied between 20% and 30%. As shown in the table 4.7, the flexural properties of the composites which were fabricated by the injection moulding showed superior flexural strength and flexural modulus values to that of the compressions moulded composites.

Table 4.7 Effect of moulding process on the flexural properties

Type of Moulding	Fibre/ MAPP Content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
Injection Moulding	Kenaf20/ MAPP2	59.8 ± 0.42	3.3 ± 0.11
	Kenaf30/ MAPP2	63.9 ± 0.38	4.3 ± 0.19
Compression Moulding	Kenaf20/ MAPP2	56.5 ± 0.73	2.4 ± 0.22
	Kenaf30/ MAPP2	57.3 ± 0.55	3.1 ± 0.18

Figure 4.7 shows the effects of the moulding process on the flexural strength. Two different percentages of kenaf fibres were incorporated into the PP matrix. It is clear from the graph that in both cases, increasing fibre content resulted in increasing flexural strength. The composite that was moulded by injection moulding, showed a higher increment in flexural strength than that of the compression moulded composite. As kenaf fibre content increased from 20 to 30 (wt%), the flexural strength of the injection moulded composites increased from 59.8 MPa to 63.9 MPa while there was no significant change of the compression moulded composites as it only increased from 56.5 MPa to 57.3 MPa.

Figure 4.8 shows the effect of moulding process on the flexural modulus. It can be seen from the graph that the injection moulded composite resulted in higher values of flexural modulus than that of the compression moulded composite. As the fibre content increased from 20% to 30%, the flexural modulus was more significantly affected by the injection moulding than by the compression moulding process.

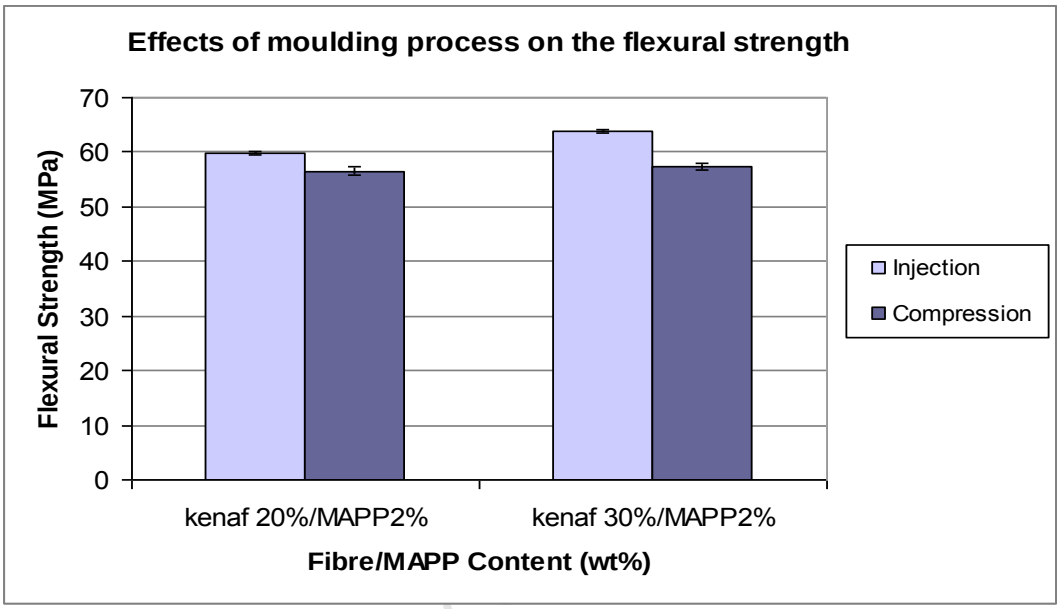

Figure 4.7 Effects of moulding process on the flexural strength

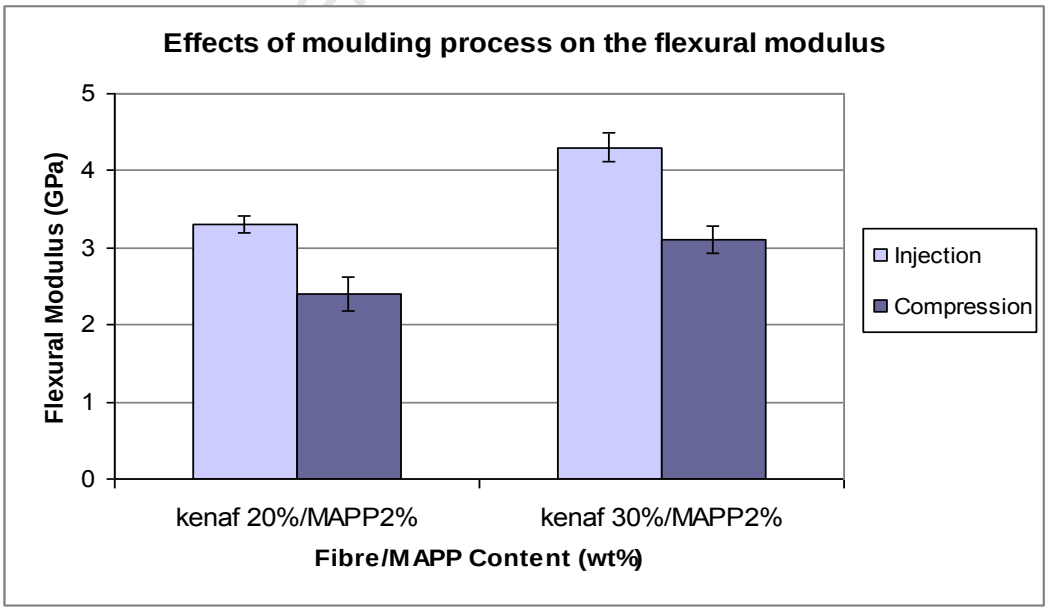

Figure 4.8 Effects of moulding process on the flexural modulus

4.2.8. Effect of Moulding Process on Impact Resistance

Figure 4.9 presents the effect of moulding process on the impact properties of kenaf fibre reinforced PP composites. It was observed that the composites produced from compression moulding had a superior impact resistance than that produced from injection moulding. It can be seen from the table 4.8 that increasing the fibre content had no significant effect on the impact resistance of the injection moulded specimen (4.04 kJ/m² and 3.95 kJ/m², respectively). On the other hand, increasing the fibre content showed a significant effect on the impact resistance of the compression moulded specimens. In this case, impact resistance dramatically reduced from 6.82 kJ/m² to 4.48 kJ/m² as fibre content increased from 20 to 30 (wt %).

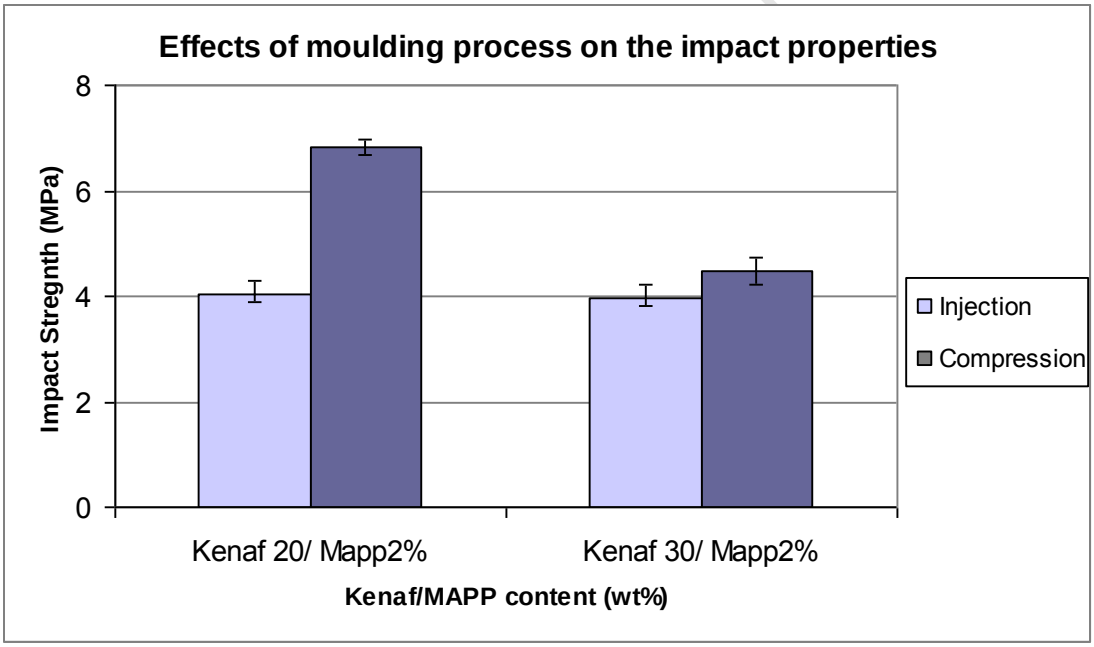

Figure 4.9 Effects of moulding process on the impact resistance

Table 4.8 Effect of moulding process on the impact resistance

Type of Moulding	Fibre/ MAPP Content (wt %)	Impact Resistance (kJ/m²)
Injection Moulding	Kenaf20/ MAPP2	4.04 ± 0.02
	Kenaf30/ MAPP2	3.95 ± 0.03
Compression Moulding	Kenaf20/ MAPP2	6.82 ± 0.14
	Kenaf30/ MAPP2	4.48 ± 0.26

4.2.9 Effect of Testing Speed on Tensile Properties

Figure 4.10 shows the effect of various testing speeds on the tensile properties of 20% kenaf fibre modified with 2% MAPP reinforced PP composites. The tensile specimens were tested at different test speeds of 0.25, 5, 100 and 200 mm/min. It can be seen from the graphs that increasing the testing speed resulted in increasing tensile strength while decreasing the ductility of the composites. As the test speed increased from 0.25 mm/min to 200 mm/min, a significant increase in tensile strength (roughly 46% increases) was observed. The tensile results are summarised in the table 4.9.

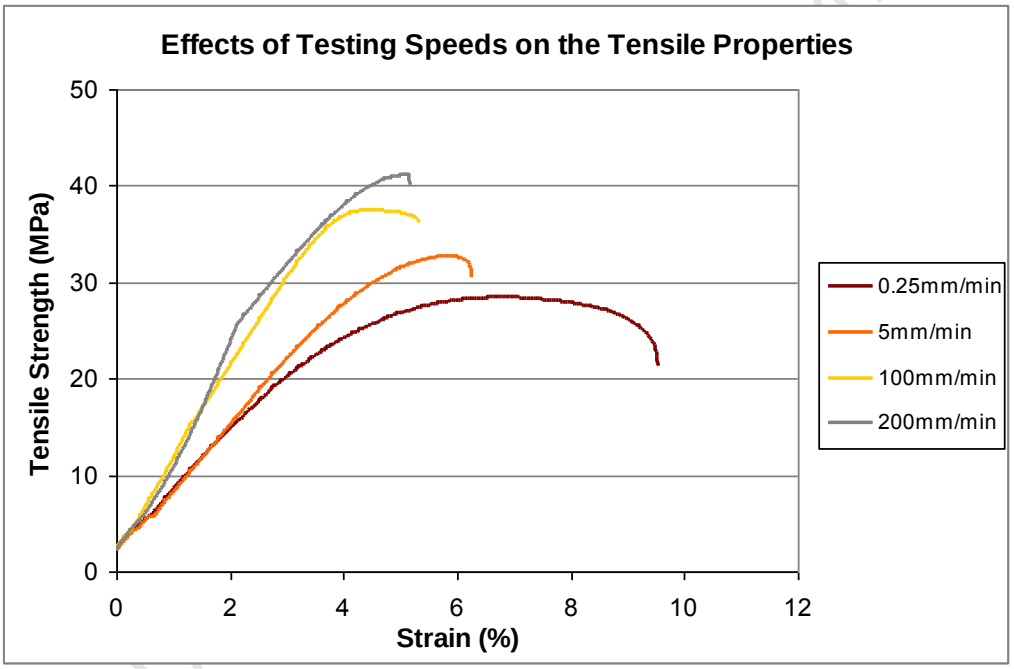

Figure 4.10 Effect of testing speed on the tensile properties

Table 4.9 Effect of testing speed on the tensile strength and failure strain

Testing Speed (mm/min)	Tensile Strength (MPa)	Strain at Break (%)
0.25	28.5 ± 0.2	9.5 ± 1.3
5	32.7 ± 0.4	6.3 ± 0.3
100	37.5 ± 0.1	5.3 ± 0.2
200	41.1 ± 1.7	5.2 ± 0.7

4.2.10 Effect of Kenaf Core Content on Flexural Properties

Table 4.10 presents the effect of kenaf core fibre (35 mm mesh grain) content on the flexural properties of kenaf fibre reinforced polypropylene composites. In each case, 4% MAPP coupled with different weight % of the kenaf core fibres were added to the polypropylene matrix. As shown in the figure 4.11, increasing the kenaf core content resulted in an improvement in both flexural strength and flexural modulus. When 10% kenaf core fibres added to the PP matrix, the flexural strength was increased by 17%. When 30% kenaf core fibres were added to the PP matrix, this increment reached a maximum value. As the slope of graph shows in the figure 4.11, increasing kenaf core content had a more significant effect on the flexural modulus than the flexural strength. When 30% kenaf core fibres were added to the PP matrix, the flexural modulus increased from 1.11 GPa to 2.41 GPa.

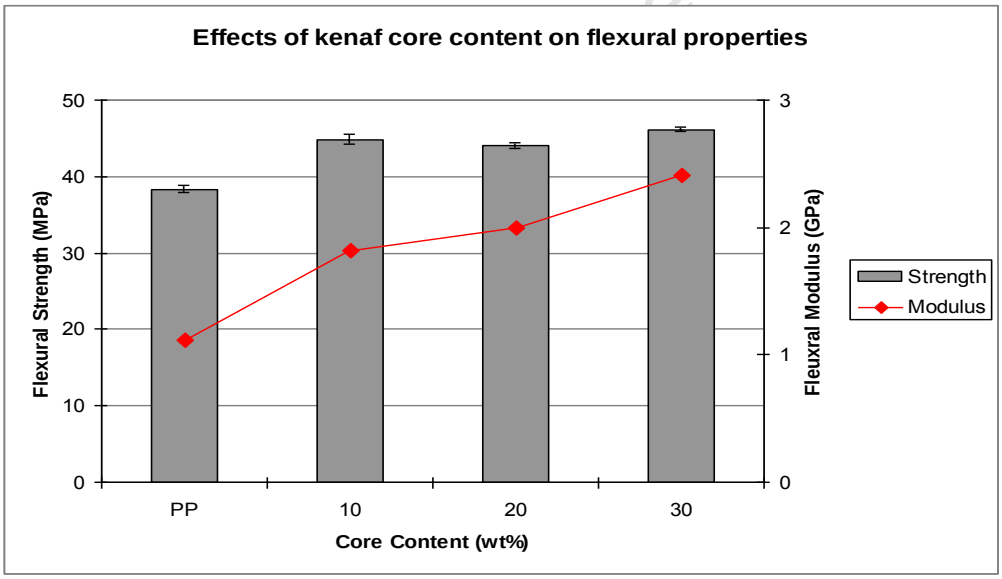

Figure 4.11 Effect of kenaf core on the flexural properties

Table 4.10 Flexural properties of the kenaf core fibre added PP composites

Core Content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0 (PP)	38.4 ± 0.5	1.1 ± 0.31
10	44.9± 0.6	1.8 ± 0.27
20	44.1 ± 0.4	2.0 ± 0.45
30	46.2 ± 0.2	2.4 ± 0.45

4.2.11 Effect of Partial Replacement of the Bast Fibres with the Core Fibres on Flexural Properties

Figure 4.12 shows the flexural properties of kenaf bast-core fibre composites. 4% MAPP modified kenaf bast and core fibres were added to the PP matrix and the total filler content were kept at 30 (wt %). It was observed from the graphs that the incorporation of kenaf core and kenaf bast fibres into the PP matrix resulted in a significant improvement in the flexural strength and the flexural modulus of the polypropylene composite.

In order to produce composite materials with a lower density, an attempt was made to replace some of the kenaf bast fibres with kenaf core fibres. In each case, the total filler content was kept at 30%. As shown in figure 4.12, replacement of kenaf bast fibres with kenaf core fibres resulted in an increase in flexural strength and flexural modulus as compare to that of the unfilled PP. When 20% of the bast fibres was replaced with core fibres (bast10/ core20), a flexural strength of about 49.2 MPa was observed whereas replacement of 10% bast fibres with core fibres (bast20/ core10) resulted in a flexural strength of about 53.1 MPa. This suggest that the amount of kenaf bast fibres present in the composite have more significant effect on the flexural properties than that of the kenaf core fibres. In other words, a higher the percentage of kenaf bast fibres in the composite, resulted in higher flexural strength as well as flexural modulus.

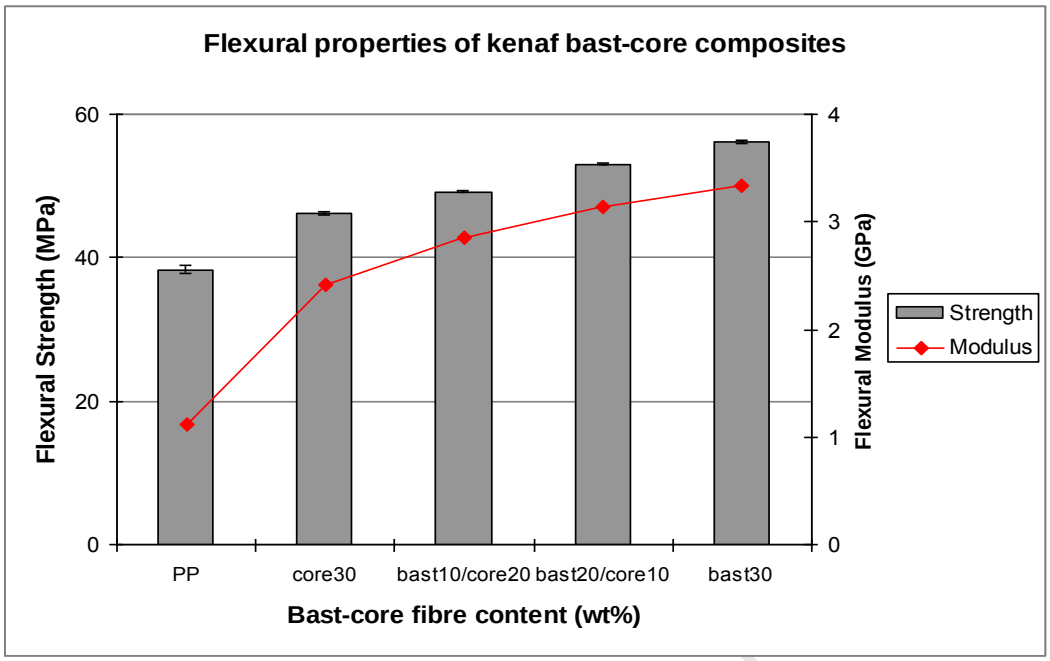

Figure 4.12 Effect of kenaf bast and core fibre content on the flexural properties

Table 4.11 Flexural properties of kenaf bast and core fibre added to PP composites

Bast fibre content (wt %)	Core fibre content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0	0	38.4 ± 0.5	1.1 ± 0.31
0	30	46.2 ± 0.2	2.4 ± 0.45
10	20	49.2 ± 0.03	2.9 ± 0.66
20	10	53.1 ± 0.1	3.1 ± 0.40
30	0	56.2 ± 0.2	3.3 ± 0.25

4.2.12 Effect of MAPP Content on the Flexural Properties of Kenaf Bast/Core Fibre Reinforced Composites

As previously shown in the figure 4.12, the replacement of 10% kenaf bast fibre with kenaf core fibre (total filler content kept at 30%) resulted in a decreased flexural strength as compared to that of the 30% kenaf bast fibre reinforced PP composites. In this case, the fibres were modified with 4% MAPP coupling agent. In order to improve the flexural strength of composites closer to the flexural strength of 30% bast fibre reinforced composites, a higher percentage of MAPP coupling agents were applied.

As shown in the figure 4.13, when the 6% of MAPP coupling agent was applied to the composite of bast20/core10, the flexural strength increased from 53.1 MPa to 56.9 MPa which was superior to that of the flexural strength of 30% bast fibre incorporated PP composite.

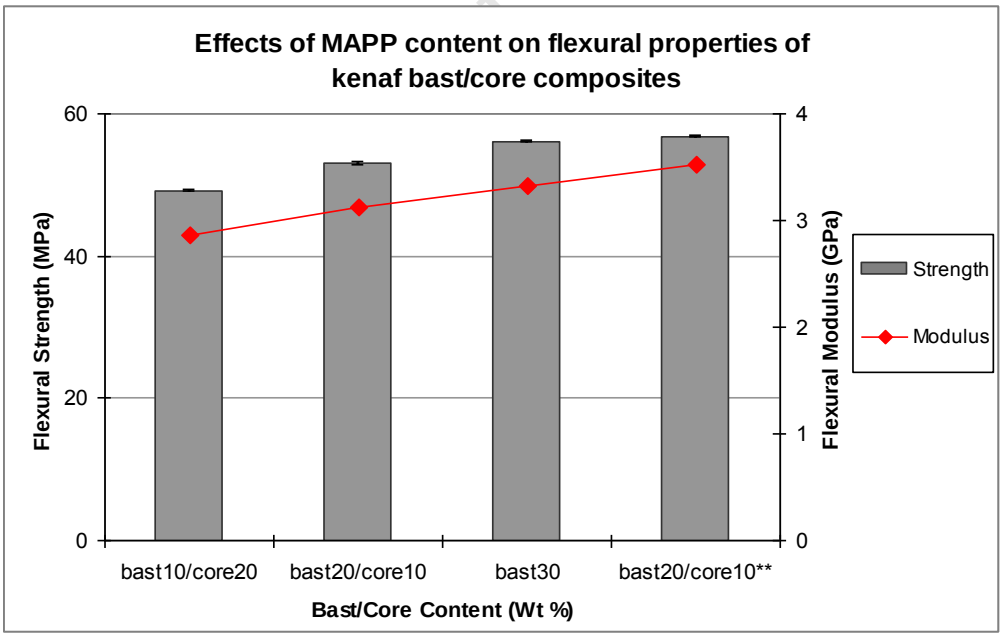

Figure 4.13 Effect of MAPP content on the flexural strength of the composites (** refers to composite modified with 6% MAPP)

4.2.13 Effect of Kenaf Core Content on the Tensile Properties

Figure 4.14 presents the effects of additions kenaf core content to the tensile properties of the polypropylene matrix. Core fibres were modified with 4% MAPP coupling agent to improve the adhesion between the core fibre and the PP matrix. The core contents were varied between 10 and 30 (wt %). Virgin PP is very ductile and has a failure strain higher than 70%. Increasing the filler content resulted in significant decreases in failure strain of the composites. Unlike the increased tensile strength obtained for the kenaf bast fibres reinforced composites, the addition of kenaf core fibres did not result in a significant increase in the tensile strength. As the core filler content increased from 0 to 30%, there was no significant increase in tensile strength.

In order to improve the tensile strength of kenaf core fibre filled PP composite, kenaf bast fibres were added. As clearly shown in figure 4.14, the addition of bast fibre resulted in an improvement of the tensile strength. The total filler content was kept at 30%. As the bast fibre content increased from 0 to 20%, the tensile strength also increased (see table 4.12).

In order to find the composition of kenaf fibre reinforced PP composites with even lower density than that of the bast fibre reinforced composites, an attempt was made to partially replace the bast fibres with core fibres. Since filler content of 30% resulted in a maximum tensile strength (see figure 4.1), test specimens were prepared with a total filler content of 30%. The polypropylene matrix was modified with 4% MAPP to improve the adhesion between matrix and fibres. The tensile strength of the 30% kenaf bast fibre reinforced composite was 32.8 MPa (see table 4.13).

When 10% of the bast fibres were replaced with core fibres (bast20/core10/MAPP4), the tensile strength decreased to 30.6 MPa. When 20% of the bast fibres were replaced with core fibres (bast10/core20/MAPP4), tensile strength dramatically decreased to 25.2 MPa.

When the bast20/core10 composite was modified with 6% MAPP coupling agent, however, it resulted in a significant improvement in tensile strength. The tensile strength increased to 33.6 MPa which is even higher than that of the 30% bast fibre reinforced PP composites (see figure 4.15).

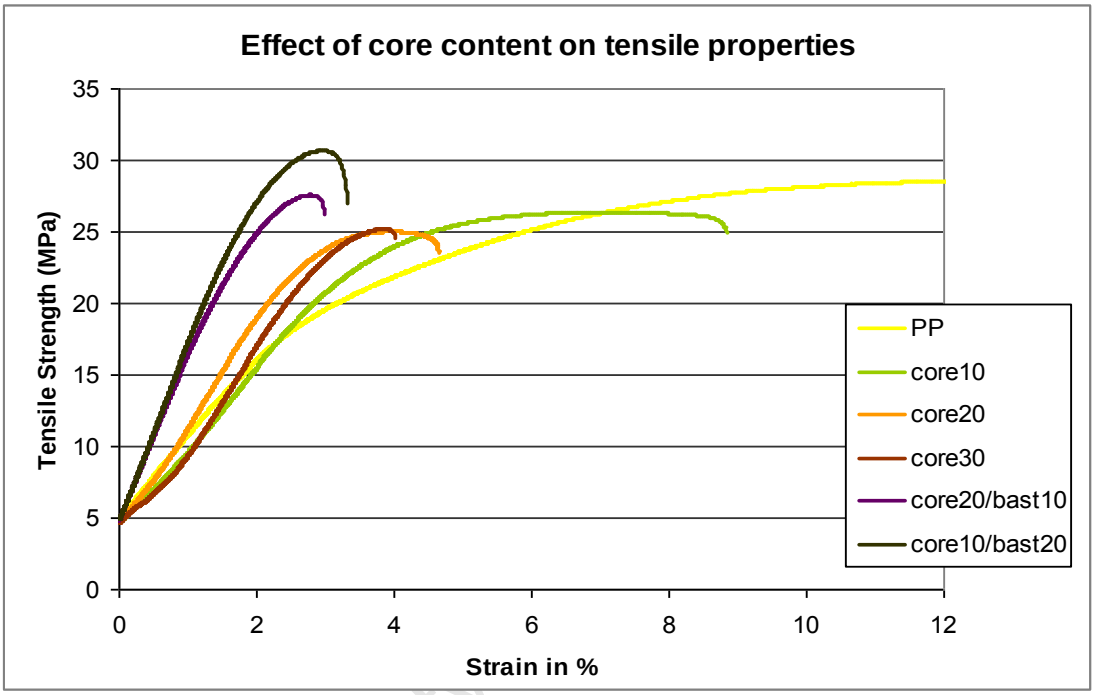

Figure 4.14 Effect of kenaf core content on the tensile properties of the PP

Table 4.12 Tensile properties of the kenaf core fibre added PP composites

Fibre Content (wt %)	Average Tensile Strength (MPa)	Strain at Break (%)
0	28.4 ± 0.2	≥70
Core10	26.3 ± 0.1	8.9 ± 1.8
Core20	25.0 ± 0.7	4.7 ± 0.6
Core30	25.2 ± 0.5	4.0 ± 0.3
Core20/Bast10	25.2 ± 0.6	4.0 ± 0.3
Core10/Bast20	30.6 ± 0.6	3.3 ± 0.3

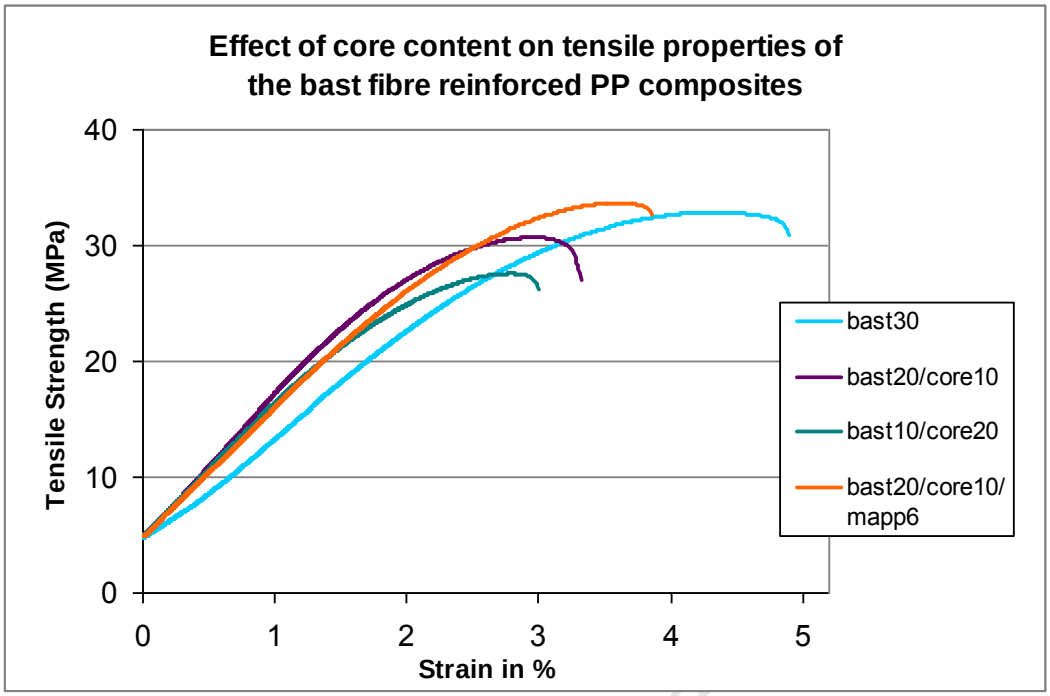

Figure 4.15 Tensile graphs of kenaf bast-core fibre filled PP composites

Table 4.13 Tensile properties of the kenaf bast-core filled composites

MAPP Content (wt %)	Fibre Content (wt %)	Average Tensile Strength (MPa)	Strain at Break (%)
4	Bast30	32.8± 0.9	4.9 ± 0.5
4	Bast20/Core10	30.6 ± 0.6	3.3 ± 0.3
4	Bast10/Core20	25.2 ± 0.6	4.0 ± 0.3
6	Bast20/Core10	33.6 ± 0.2	3.9 ± 0.4

4.2.14 Effect of Kenaf Core Content on the Impact Resistance

Figure 4.16 presents the effect of the addition of kenaf core fibres on the impact resistance of the PP matrix. In order to improve the adhesion between the kenaf core fibre and the PP matrix, 4% MAPP coupling agent was applied. The addition of kenaf core fibres resulted in a decrease in the impact resistance of the PP matrix. When 10% kenaf core fibres were added to the PP matrix, the impact resistance decreased from 3.41 kJ/m^2 to 2.46 kJ/m^2. Although the initial addition of kenaf core fibres resulted in a decrease in impact resistance of the PP composites, increasing the kenaf core content from 10% onward led to a gradual improvement in the impact resistance of the composite. As the kenaf core content increased from 10 to 30 (wt %), the impact resistance increased from 2.36 kJ/m^2 to about 2.89 kJ/m^2.

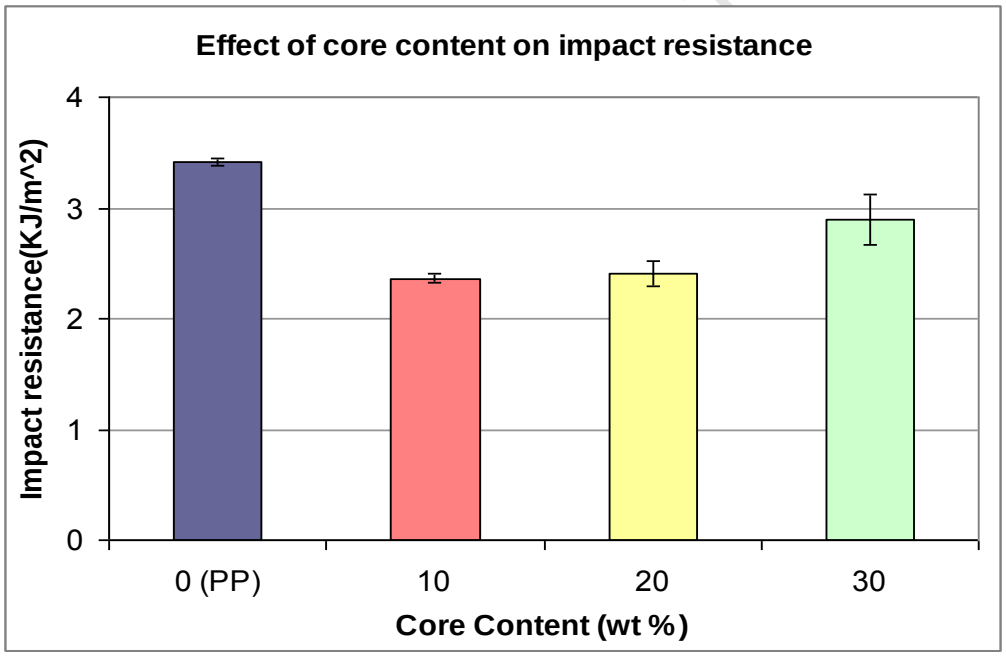

Figure 4.16 Effect of kenaf core content on the impact resistance of PP

Figure 4.17 presents the effects of partial replacement of kenaf bast fibres with kenaf core fibres on the impact resistance. Unexpectedly, introducing kenaf bast fibres into the PP matrix resulted in an increased impact resistance compared to that of the unfilled PP matrix. Incorporation of 30% bast fibres improved the impact resistance from 3.41 kJ/m^2 to 4.18 kJ/m^2.

On the other hand, as the percentage of replacement of the bast fibre increased further, the impact resistance of the composites decreased. When 10% of bast fibres were replaced with core fibres, impact resistance decreased from 4.18 kJ/m^2 to 3.45 kJ/m^2 which is still higher than that of the unfilled PP matrix. Further increasing of core fibre content to 20%, however, resulted in a decrease in impact resistance to 3.11 kJ/m^2 which is slightly lower than that of the unfilled PP matrix.

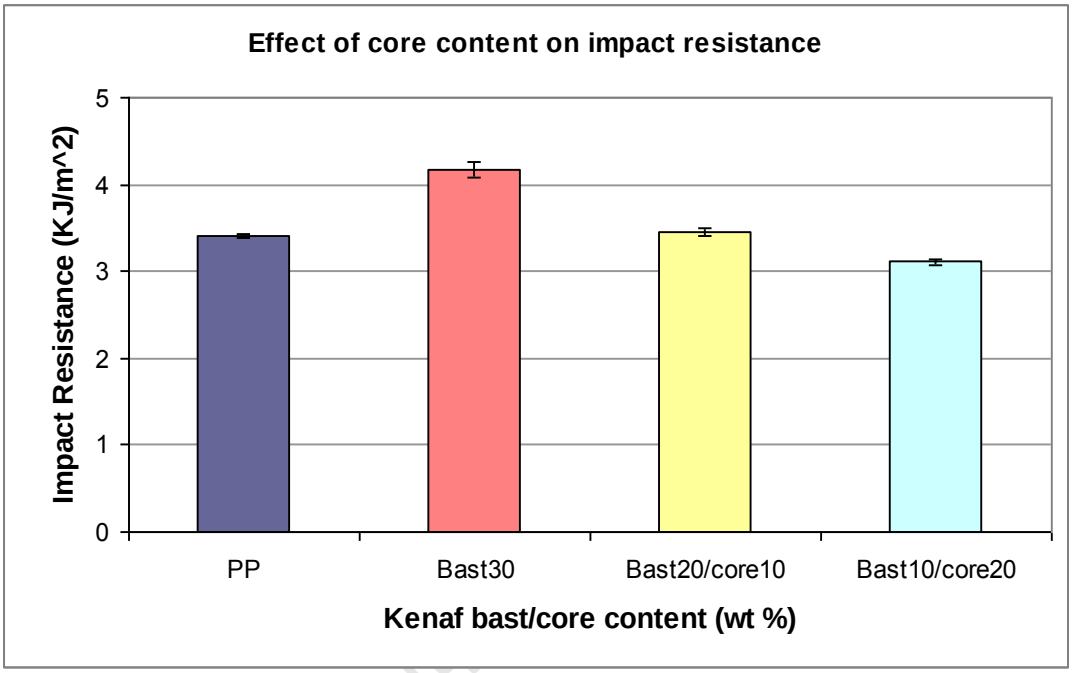

Figure 4.17 Effect of kenaf core content on the impact resistance of the kenaf bast fibre reinforced PP composites

4.2.15 Effect of Kenaf Core (Powder) on the Flexural Properties

Figure 4.18 shows the effect of the addition of kenaf core on the flexural properties of PP composites. In this case, the powdered form of kenaf core was used. Unexpectedly, the addition of 20% and 30% kenaf core into the 30% kenaf bast fibre reinforced PP composite with 2% MAPP resulted in reduction of the flexural strength. However, the addition of 20% kenaf core to the composite showed an increase in the flexural modulus value (4.98 GPa). When the 30% core was added, flexural modulus decreased to about 4.70 GPa, and this value is still higher than that of the composite without the core (3.15GPa). Table 4.10 summaries the values of flexural strength and modulus with respect to the addition of core content.

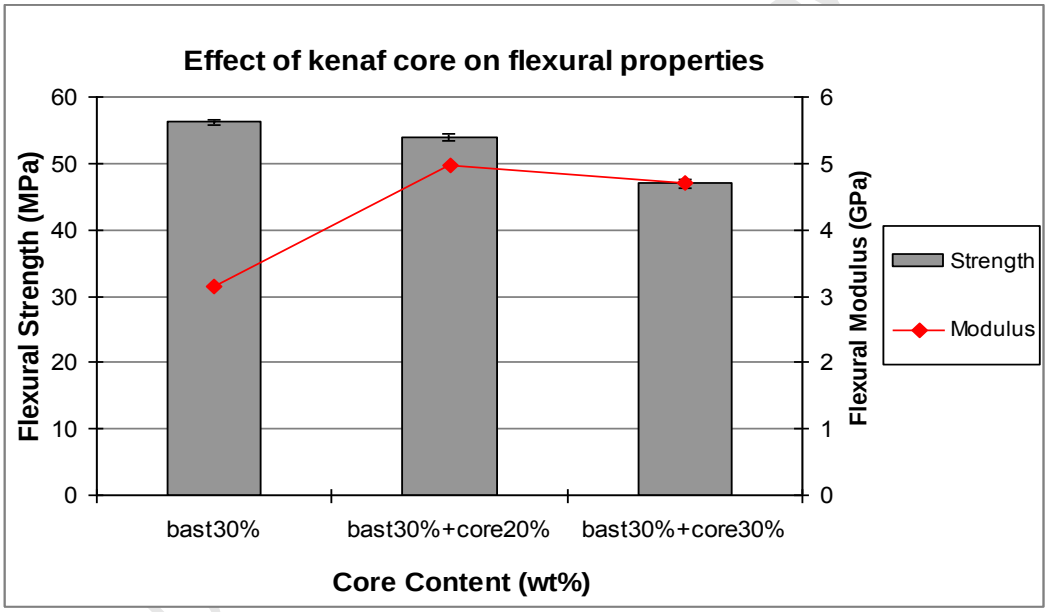

Figure 4.18 Effect of kenaf core content on flexural properties

Table 4.10 Effect of kenaf core on flexural strength and modulus

Core Content (wt %)	Flexural Strength (MPa)	Flexural Modulus (GPa)
0	57.3 ± 0.5	3.1 ± 0.38
20	53.9 ± 0.6	4.9 ± 0.37
30	46.9 ± 0.7	4.7 ± 0.66

4.2.16 Effect of Kenaf Core (Powder) on the Impact Resistance

Figure 4.19 shows the effect of kenaf core powder on the impact resistance of 30% kenaf fibre reinforced PP composites. The addition of kenaf core gradually increased the impact resistance of the composites. These values are summarised in the table 4.11.

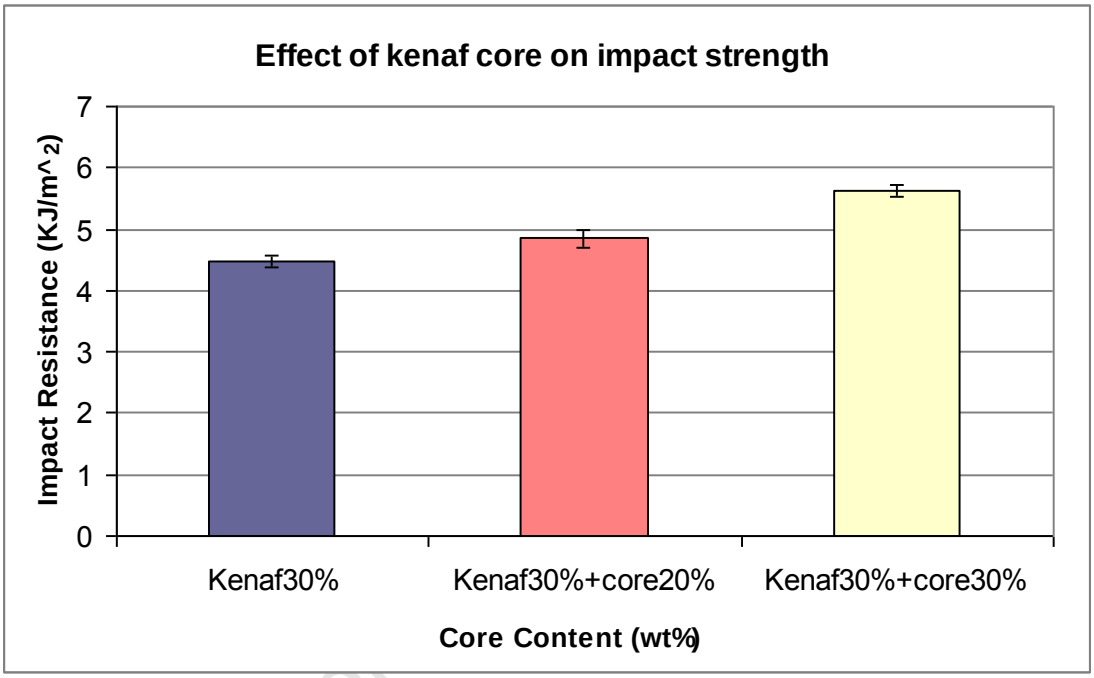

Figure 4.19 Effect of kenaf core on impact strength

Table 4.11 Effect of core content on the impact strength

Core Content (wt %)	Impact Strength (kJ/m²)
0	4.4 ± 0.26
20	4.8 ± 0.39
30	5.6 ± 0.24

4.2.17 Comparison between Local and International Kenaf Fibre Reinforced PP Composites

The mechanical properties of the local kenaf fibre reinforced polypropylene composite were compared with the international kenaf fibre reinforced composites. The flexural strength, flexural modulus and impact resistance of each composite were measured and the results are reported in table 4.12. For all the mechanical properties observed, the international kenaf fibre reinforced composite showed slightly superior flexural properties than that of the local kenaf fibre reinforced composite. However, the flexural modulus and impact resistance of the local kenaf fibre reinforced composites compared well with the international kenaf fibre reinforced composites.

Table 4.12 Comparison between local and international kenaf fibre composite

Mechanical Properties	Local Kenaf/PP Composites	International Kenaf/PP Composites
Flexural Strength (MPa)	50.5 ± 0.36	57.3 ± 0.49
Flexural Modulus (GPa)	2.7 ± 0.47	3.2 ± 0.38
Impact Resistance (kJ/m²)	3.9 ± 0.33	4.5 ± 0.26

4.4 THERMAL PROPERTIES OF THE COMPOSITES

4.4.1 Effect of Fibre Content on the Thermal Properties

The thermal properties of the compression moulded kenaf fibre reinforced polypropylene composites has been analysed by DSC. Thermal parameters of the composites such as melting temperature (Tm), crystallisation temperature (Tc), heat of fusion (ΔH_f) and degrees of crystallisation (Xc) were identified. Various loadings (20 to 40 wt %) of kenaf fibres were incorporated into the polypropylene matrix and each of the batches was modified with 2% MAPP coupling agent. The heat of fusion (ΔH_f) can be determined by measuring the area under the endothermic peak [54, 55]. These values are automatically obtained from the instrument.

Table 4.13 presents the effect of fibre content on the thermal properties of kenaf fibre reinforced polypropylene composites. The addition of fibres resulted in increasing melting and crystallisation temperatures. Table 4.13 shows that as fibre content increased from 20 to 30% (wt %), heat of fusion as well as degree of crystallisation increased. These increasing values were shown as a broader melting and crystallisation peak in the figure 4.20. When the 30% kenaf fibres were incorporated into the composites, both the heat of fusion and degree of crystallisation reached maximum values. Further increases of fibre content to 40%, resulted in a decrease in the heat of fusion and degree of crystallisation. This minimum ΔH_f value was shown as the narrowest peak in the figure 4.21.

Table 4.13 Effect of fibre content on the thermal properties of kenaf/PP composites

Fibre Content (wt %)	Tc (°C)	Tm (°C)	ΔH_f (J/g)	Xc (%)
20	119.2	164.1	55.0	26.3
30	119.6	164.4	64.0	30.6
40	120.0	164.9	42.1	20.1

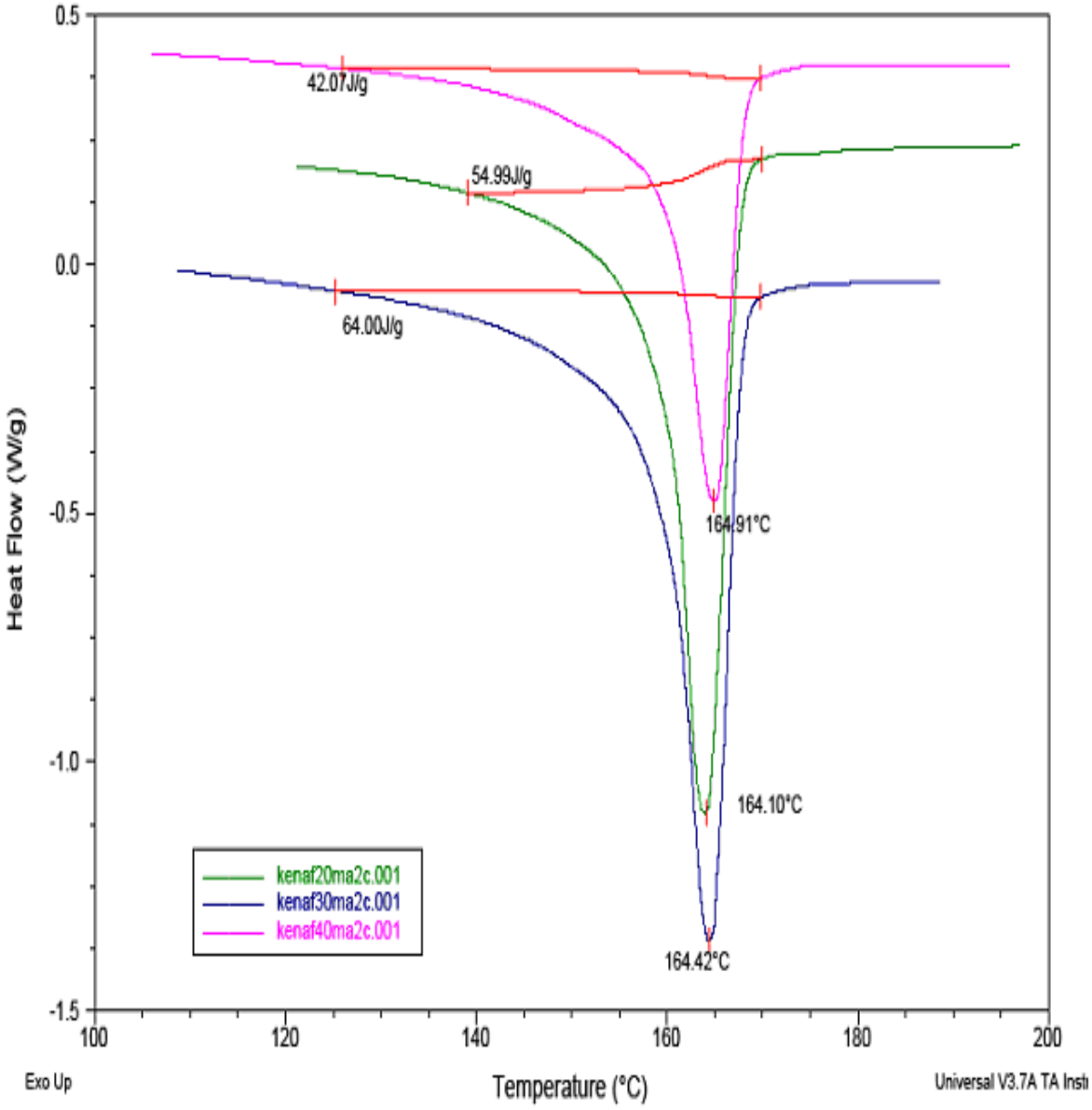

Figure 4.20 DSC heating scans (Tm) of kenaf/ PP composites

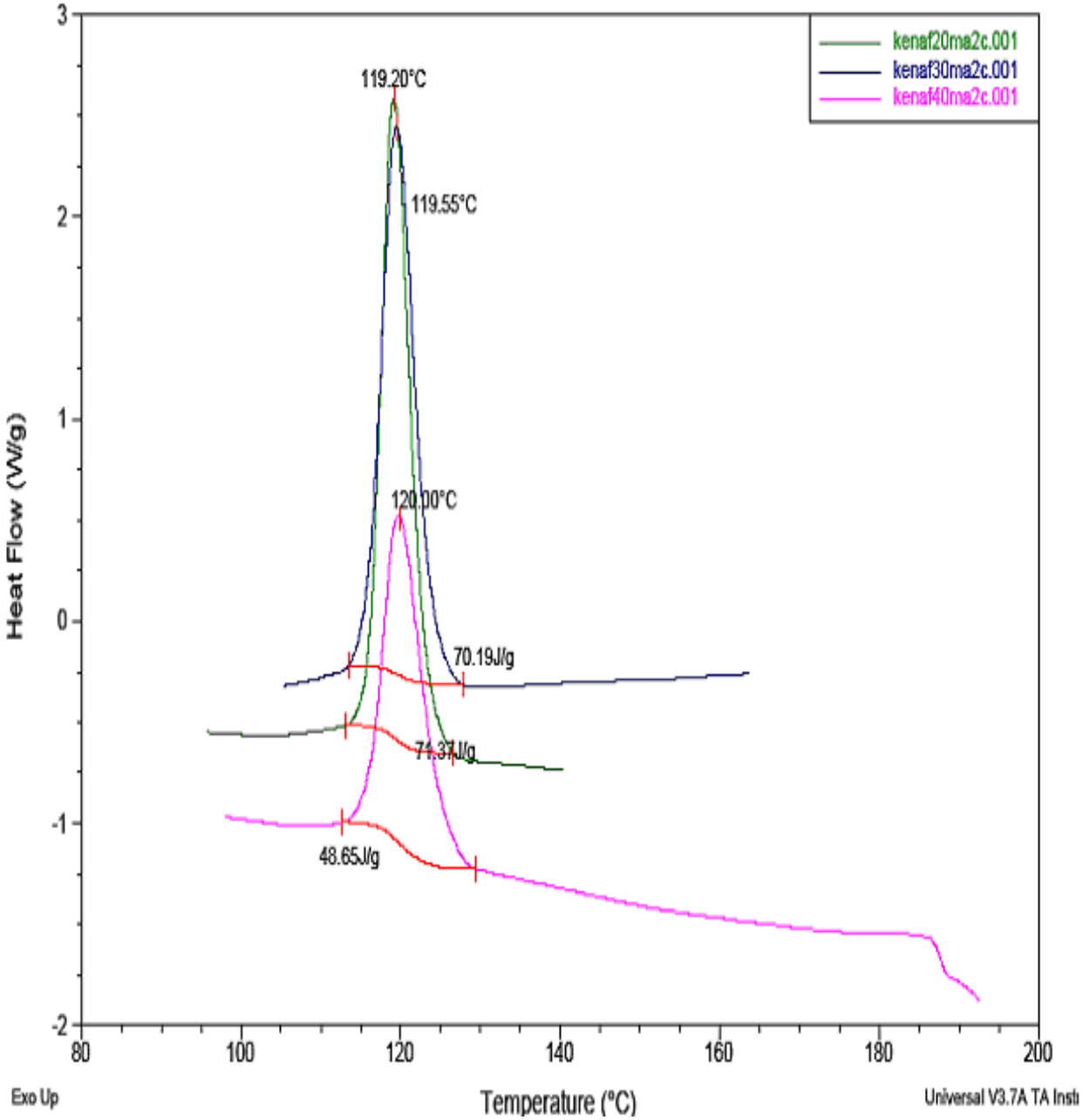

Figure 4.21 DSC cooling scans (Tc) of kenaf/ PP composites

4.4.2 Effect of MAPP Content on the Thermal Properties

The effect of MAPP content on the thermal properties of kenaf fibre reinforced polypropylene composites has been analysed by DSC. Thermal parameters of the composites such as melting temperature (Tm), crystallisation temperature (Tc), heat of fusion (ΔH_f) and degrees of crystallisation (Xc) were identified with respect to changes in MAPP content. The MAPP content varied between 3 and 5 (wt %) and 30 (wt %) kenaf fibres were incorporated into each batch. The heat of fusion (ΔH_f) can be determined by measuring the area under the endothermic peak [54, 55].

Table 4.14 presents the effect of MAPP content on the thermal properties of kenaf fibre reinforced polypropylene composites. The addition of MAPP coupling agent gradually decreased the melting and the crystallisation temperatures of the composites. Table 4.14 shows that as the MAPP content increased from 3 to 4 (wt %), heat of fusion as well as degree of crystallisation increased. These increasing values were shown as a broader melting and crystallisation peaks in figure 4.23. As shown in the table 4.14, the composite modified with 4% MAPP coupling agent had a maximum heat of fusion and degree of crystallisation. However, with further increase of the MAPP content to 5% resulted in decreasing heat of fusion and degree of crystallisation, which was still higher than that of the composite modified with 3% MAPP.

Table 4.14 Effect of MAPP content on the thermal properties of kenaf/PP composites

MAPP Content (wt %)	Tc (°C)	Tm (°C)	ΔH_f (J/g)	Xc (%)
3	119.5	165.7	46.5	22.2
4	119.2	165.7	54.5	26.0
5	118.1	164.0	51.7	24.7

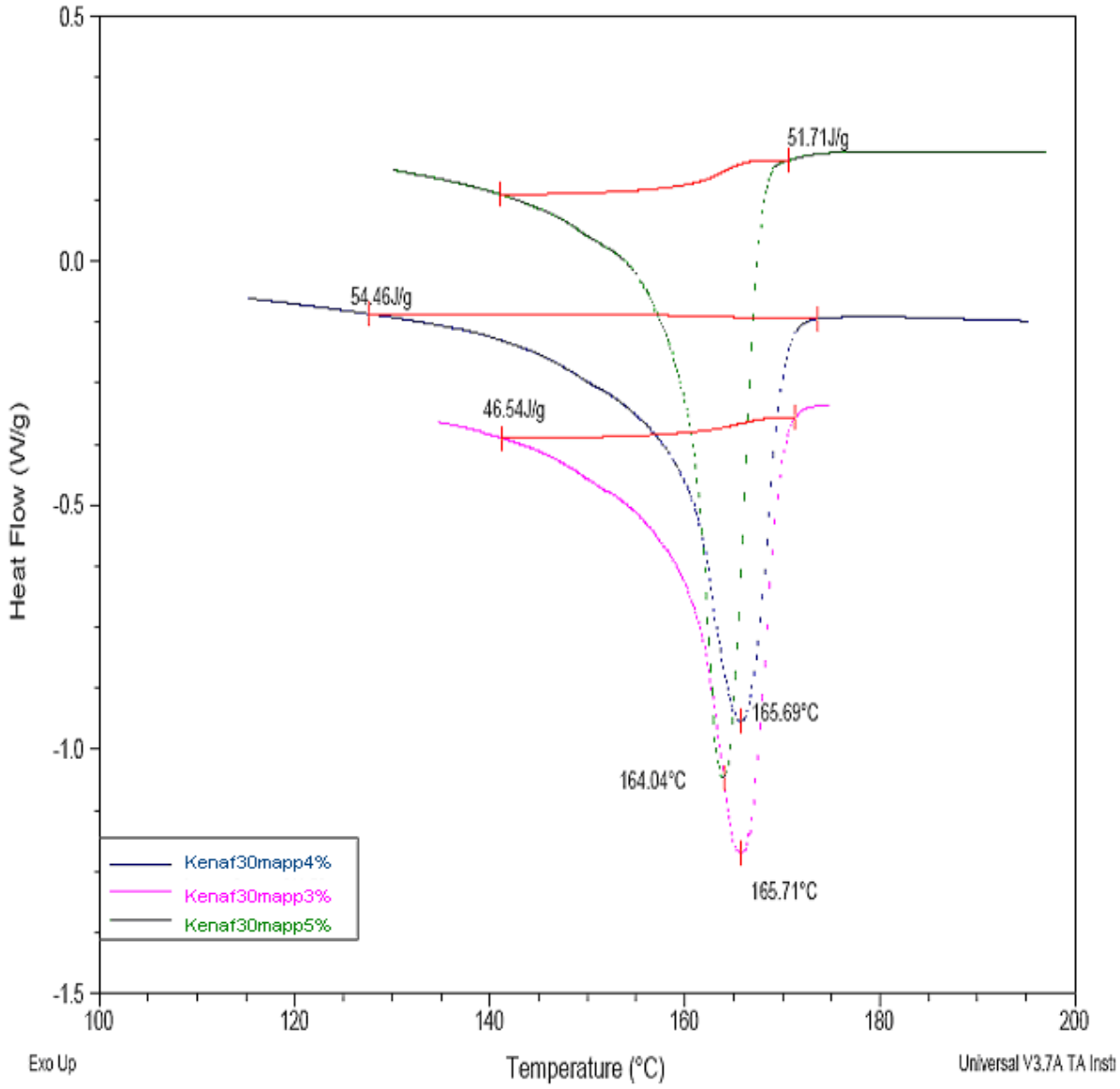

Figure 4.22 DSC heating scans (Tm) of kenaf/PP composites

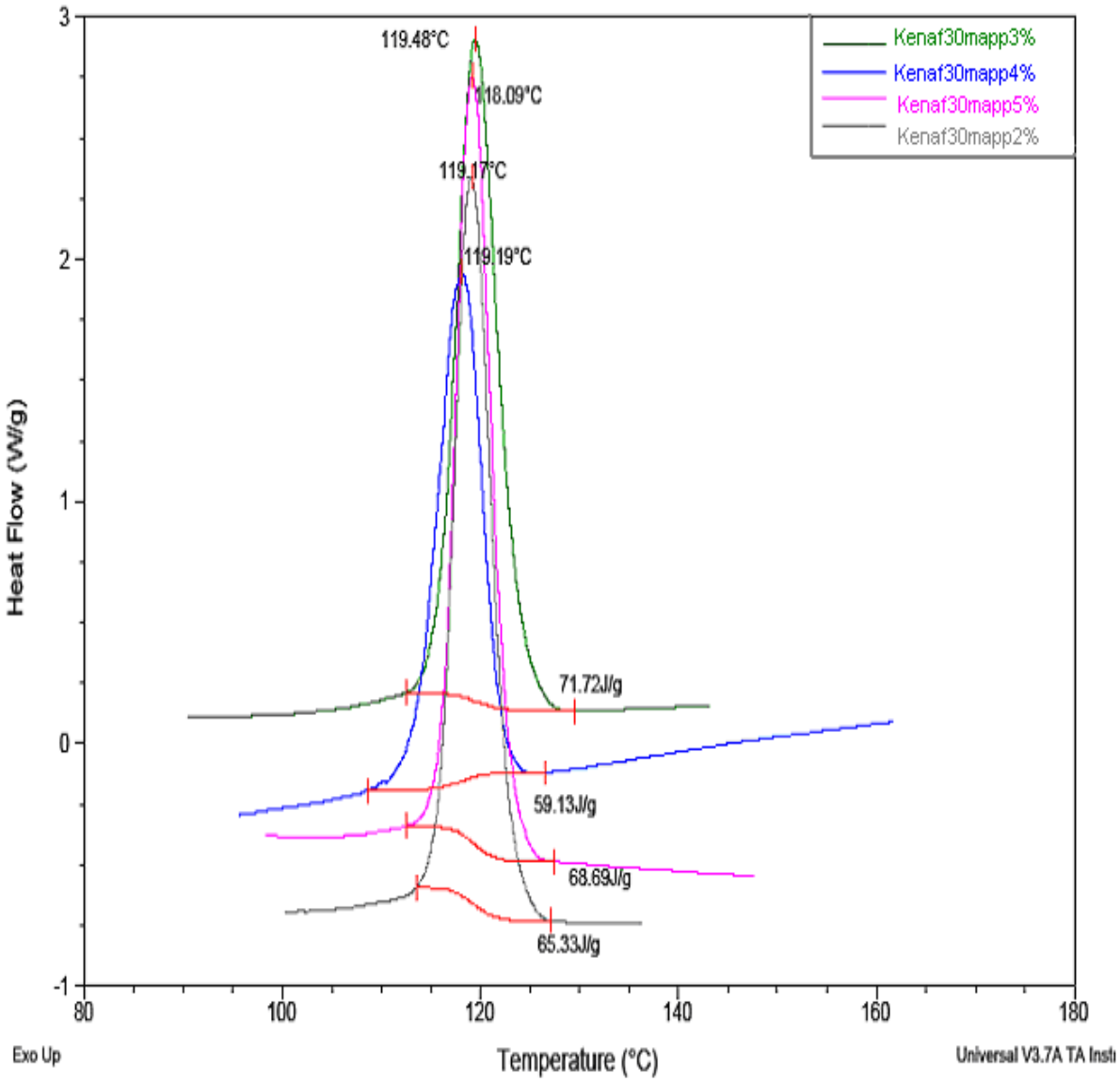

Figure 4.23 DSC cooling scans (Tc) of kenaf/PP composites

4.4.3 Effect of Kenaf Core Content on the Thermal Properties

The effect of kenaf core content on the thermal properties of PP was investigated by DSC. In order to improve the compatibility between the kenaf core fibres and the PP matrix, fibres were modified with 4% MAPP coupling agent. From the DSC scans, the melting temperature (Tm), crystallisation temperature (Tc) and heat of fusion (ΔH_f) were obtained. Also, degree of crystallisation was calculated by utilising the following equation:

$$X_C = \frac{\Delta H_f}{\Delta H_f^o} \times 100$$

ΔH_f = heat of fusion, ΔH_f^o = heat of fusion of a 100% crystalline isotactic material

Table 4.15 presents the thermal properties of kenaf core filled PP matrix. The addition of core fibres into the PP matrix resulted in decreasing the crystallisation and melting temperatures. As the core fibre content increased from 10 to 30 (wt %), the heat of fusion as well as the degree of crystallinity were reduced. These decreasing values are shown as a narrower crystallisation and melting peaks in figure 4.24 and figure 4.25.

Table 4.15 Effect of core content on the thermal properties of kenaf core/PP composites

Core Content (wt %)	Tc (°C)	Tm (°C)	ΔH*f* (J/g)	Xc (%)
0	123.8	154.6	73.7	35.2
10	120.5	153.8	63.7	30.5
20	111.8	151.3	56.2	23.9
30	112.4	150.5	38.6	18.5

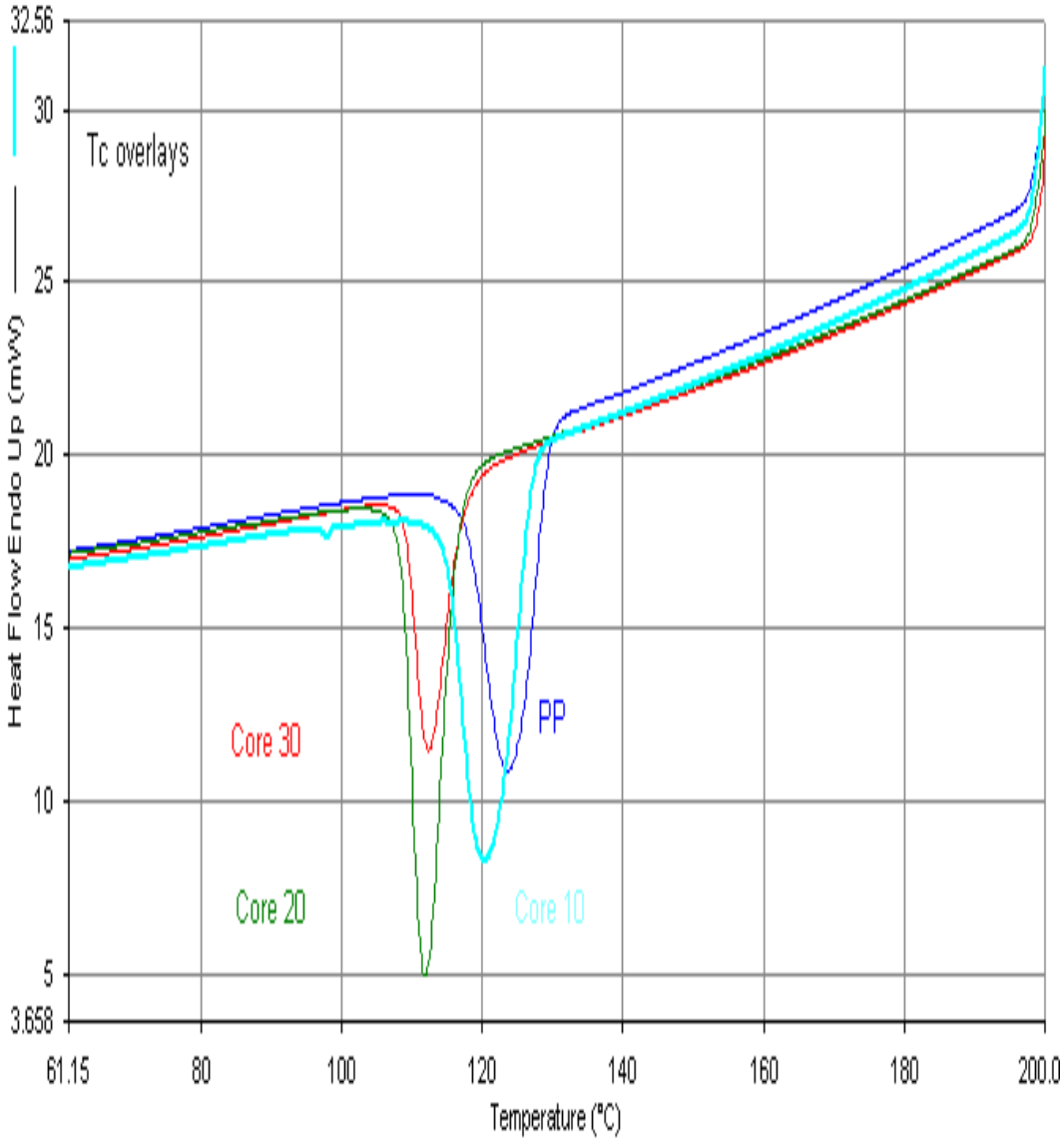

Figure 4.24 DSC cooling scans of kenaf core/PP composites

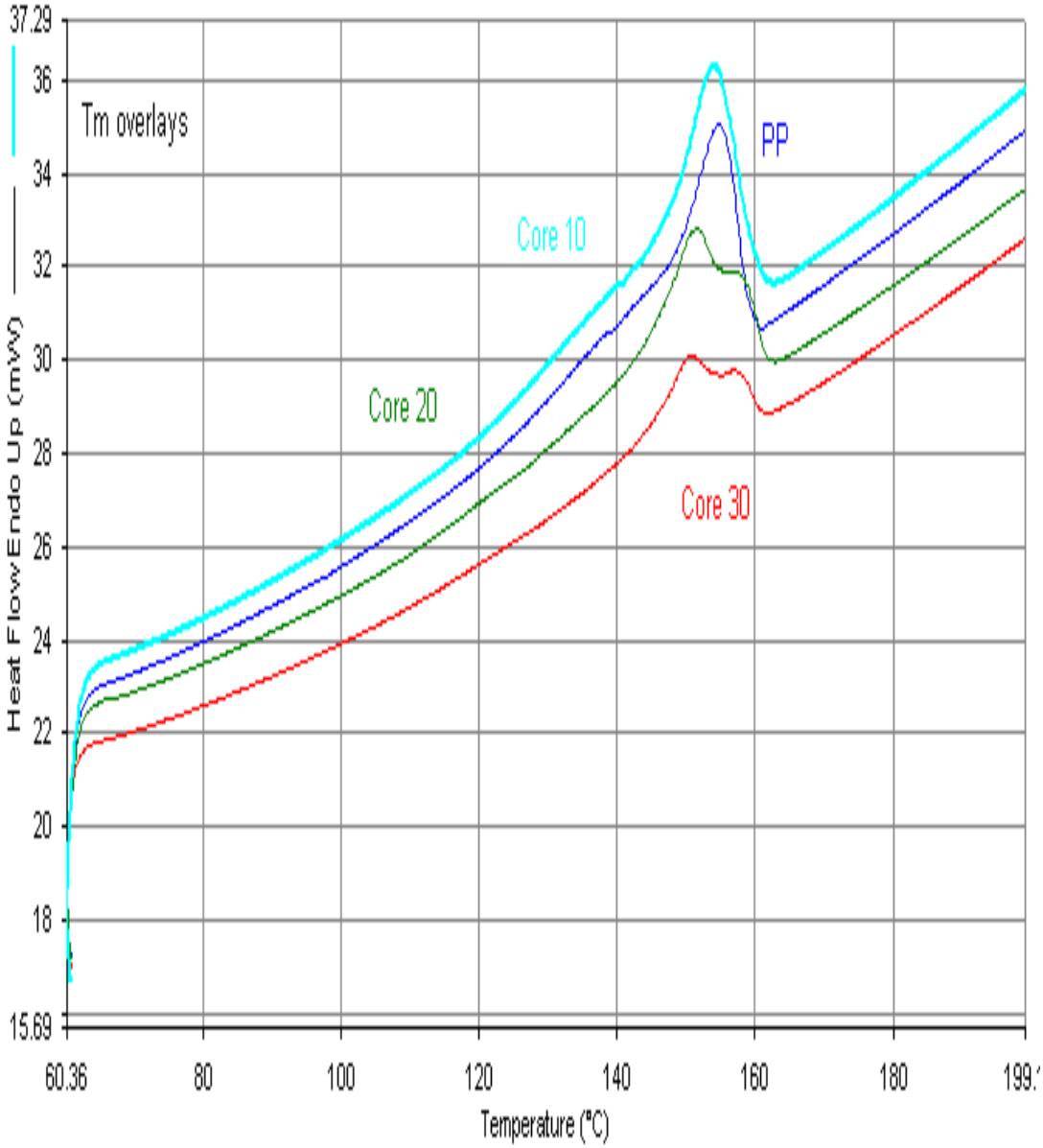

Figure 4.25 DSC heating scans of kenaf core/ PP composites

4.4.4 Effect of Partial Replacement of Kenaf Bast Fibres on the Thermal Properties

In order to identify the effect of partial replacement of bast fibres with core fibres on the thermal properties of PP composites, 10 and 20 (wt %) of bast fibres were replaced with core fibres. The total filler content was kept at 30% and the fibres were modified with 4% MAPP coupling agent. Table 4.16 shows that partial replacement of bast fibres with core fibres resulted in a decreased crystallisation temperature as well as melting temperature. These decreasing values were also observed in the heat of fusion and the degree of crystallinity. When 10% of bast fibres were replaced with core fibres, the degree of crystallinity was reduced by 2.6%. When 20% of bast fibres were replaced with core fibres, degree of crystallinity was reduced even further, by 2.8%. Decreasing values of the heat of fusion and the degree of crystallinity were shown as a narrower peak in figure 4.26 and 4.27.

When the fibres were modified with 6 (wt %) of MAPP coupling agent, the crystallisation temperature of the composite (bast 20/core10) decreased from 112.7° to 112.5°C. However, the melting temperature of the composite increased from 151.5°C to 152.3°C, which is even higher than that of the 30% bast fibre reinforced PP composites. Increasing the MAPP content resulted in an increased heat of fusion as well as degree of crystallinity. The degree of crystallinity increased from 23.9% to 24.6% which is higher than that of the 30% bast fibre reinforced PP composites.

Table 4.16 Effect of partial replacement of kenaf bast fibres on the thermal properties of bast/core composites

Bast/Core Content (wt %)	MAPP (%)	Tc (°C)	Tm (°C)	ΔH_f (J/g)	Xc (%)
30/0	4	116.2	151.8	51.3	24.5
20/10	4	112.7	151.5	50.0	23.9
10/20	4	113.3	150.4	49.9	23.8
20/10	6	112.5	152.3	51.6	24.6

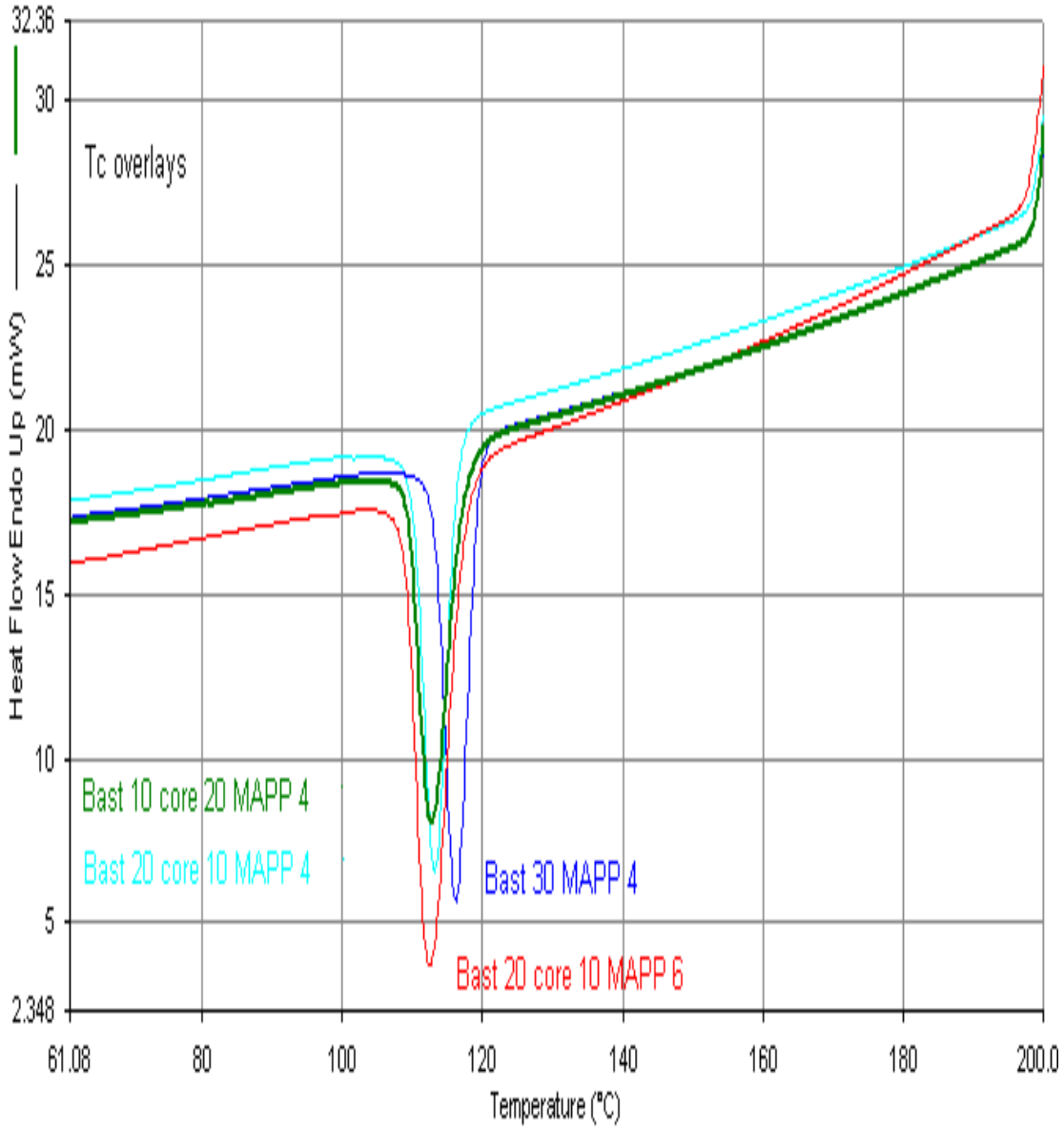

Figure 4.26 DSC cooling scans of kenaf bast /core composites

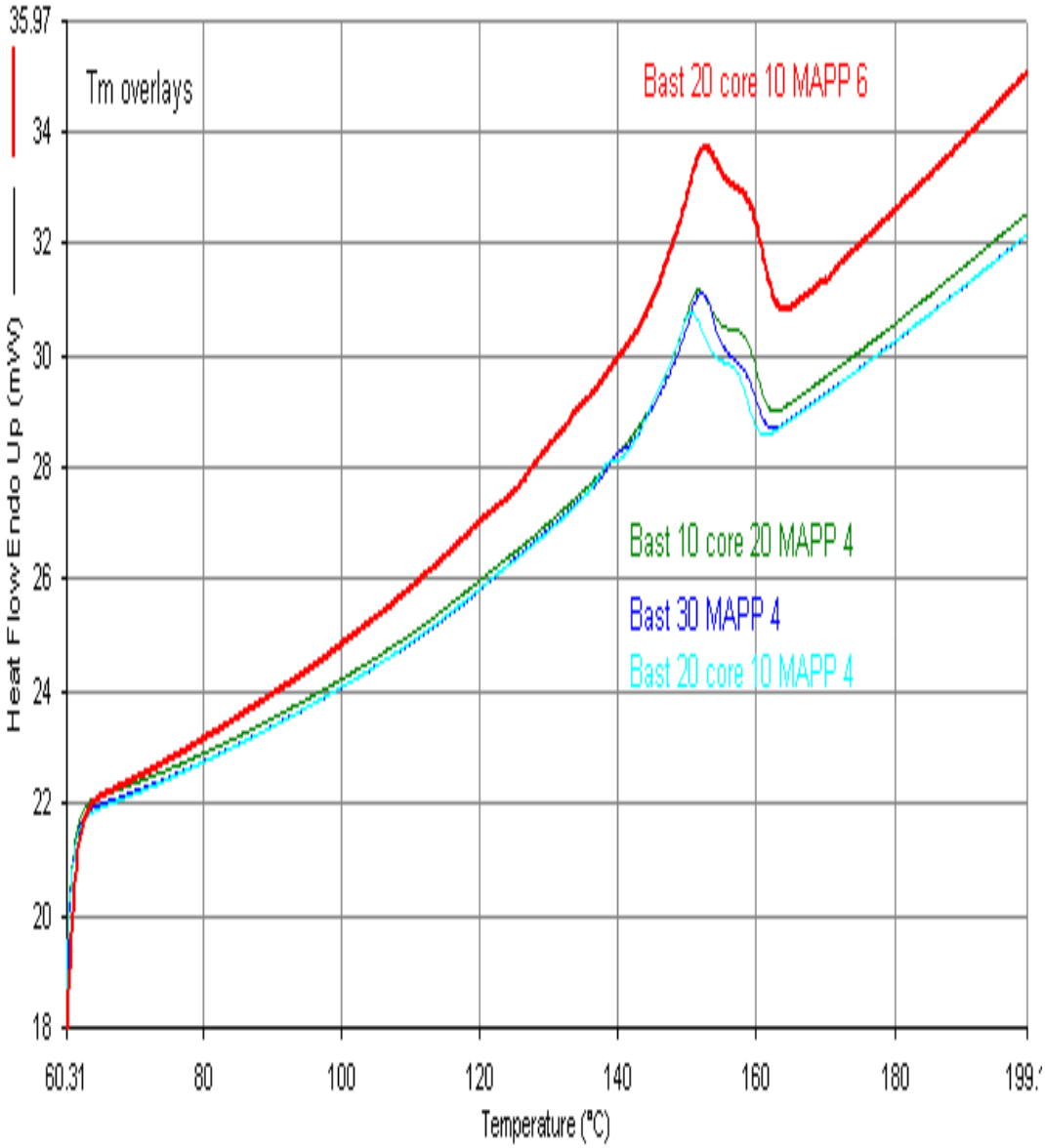

Figure 4.27 DSC heating scans of kenaf bast/ core composites

4.5 MORPHOLOGICAL PROPERTIES OF THE COMPOSITES

4.5.1 Effect of Fibre Reinforcement

The effect of fibre content on the failure mode of kenaf fibre reinforced PP composites has been studied. Figure 4.28 presents a SEM micrograph of the fracture surface of 20% kenaf fibre reinforced PP composites. The fibre-matrix debonding indicates a poor fibre-matrix adhesion and river marks shows the direction of crack propagation in the PP matrix. Figure 4.29 shows the fracture surface of 30% kenaf fibre reinforced PP composites. It was clearly observed that fibre breakage was the dominant failure mode. Delamination of the matrix indicates the occurrence of shear failure and rough fibre ends indicate that the material failed in brittle manner. Figure 4.30 presents a SEM micrograph of the fracture surface of the impact test specimens of 40% kenaf fibre reinforced PP composites. Micro-cracks on the fibre surface and rough fibre ends indicate brittle failure of material. SEM micrographs show that the fibre bunch pull-out was dominated failure mode.

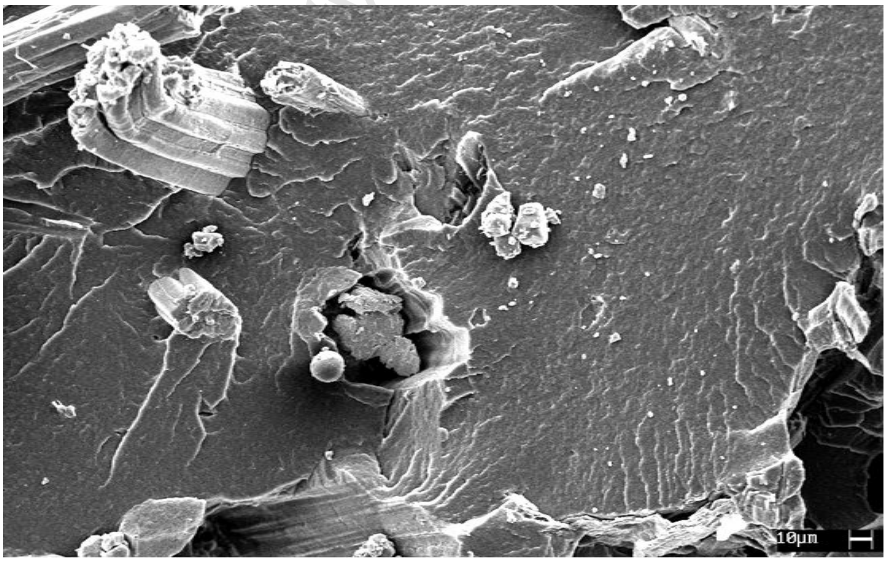

Figure 4.28 SEM micrograph of the fracture surface of the 20% kenaf fibre reinforced PP composites

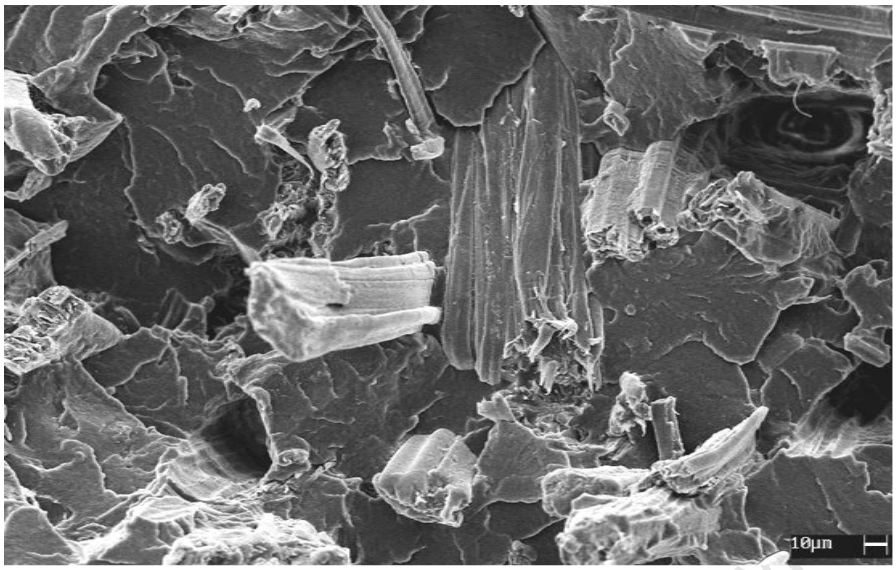

Figure 4.29 SEM micrograph of the fracture surface of the 30% kenaf fibre reinforced PP composites

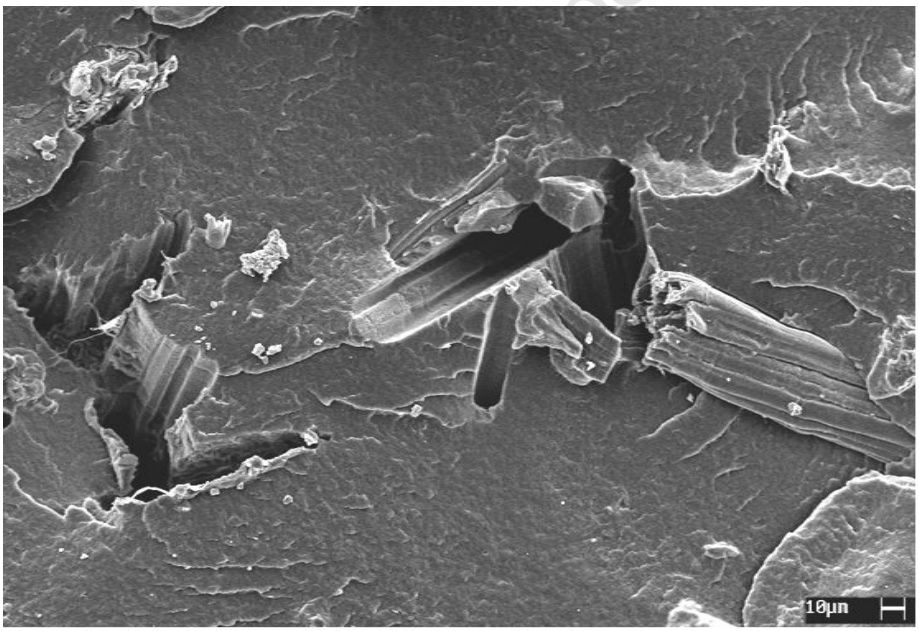

Figure 4.30 SEM micrograph of the fracture surface of the 40% kenaf fibre reinforced PP composites

4.5.2 Effect of Surface Modification

The effect of surface treatment on the failure mode of kenaf fibre reinforced PP composites was studied. As shown in figure 4.31, SEM micrographs of the untreated kenaf fibre reinforced PP composites show microscopic pits and cracks on the fibre surface which indicates poor fibre-matrix interfacial bonding. On the other hand, the MAPP treated kenaf composites showed improved adhesion between the fibres and the matrix. The extent of the improved interfacial bonding between the fibre and the matrix is indicated with an arrow in the figure 4.32.

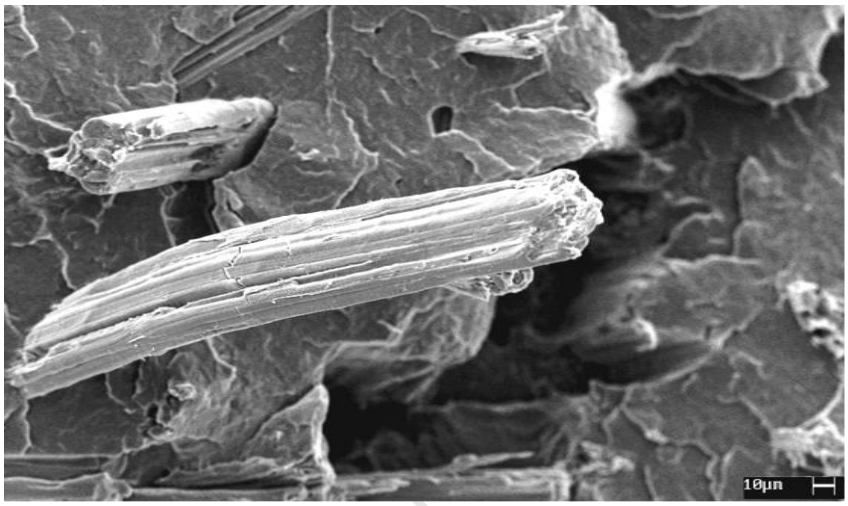

Figure 4.31 SEM micrograph of the fracture surface of untreated kenaf bast20/core10 reinforced PP composites

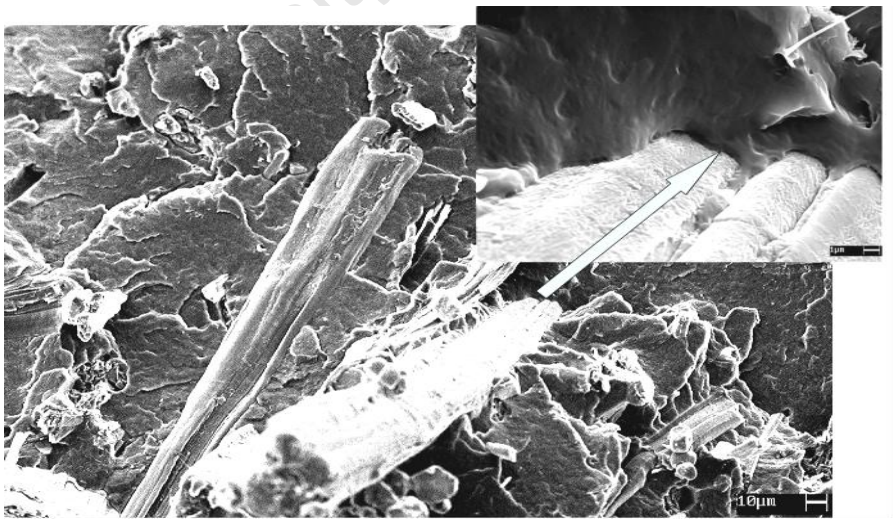

Figure 4.32 SEM micrograph of the fracture surface of MAPP (6%) treated kenaf bast20/core10 reinforced PP composites

4.5.3 Effect of Addition of Fillers (Kenaf Core)

Figure 4.33 shows a SEM micrograph of the fracture surface of 20% kenaf bast fibre reinforced PP composites. Bunches of fibre pull-out was observed. Figure 4.34 presents a SEM micrograph of the fracture surface of kenaf bast20/core10 filled PP composites. The SEM micrograph clearly shows the occurrence of debonding due to fibre pull-out. Kenaf core debonding resulted in cracking and disintegration of the matrix. Delamination indicates a poor fibre-matrix interfacial bond.

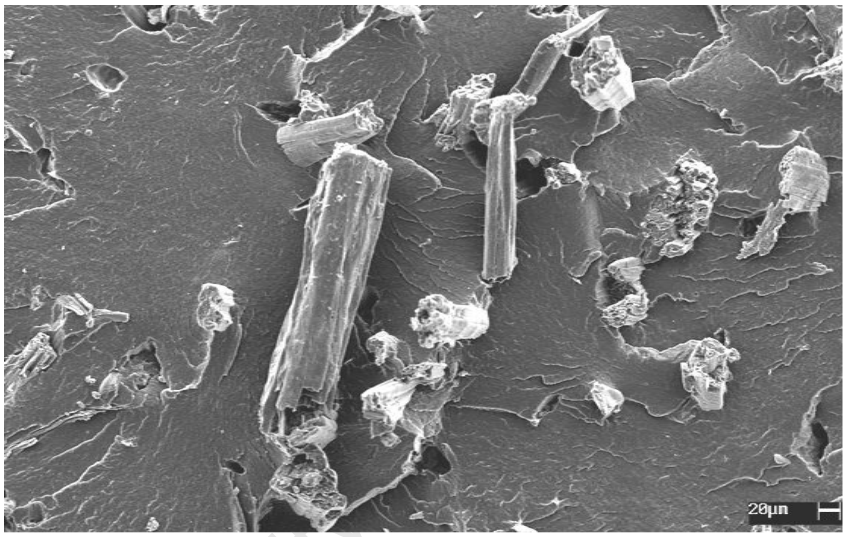

Figure 4.33 SEM micrograph of the fracture surface of kenaf bast20/MAPP4 (wt %) PP composites

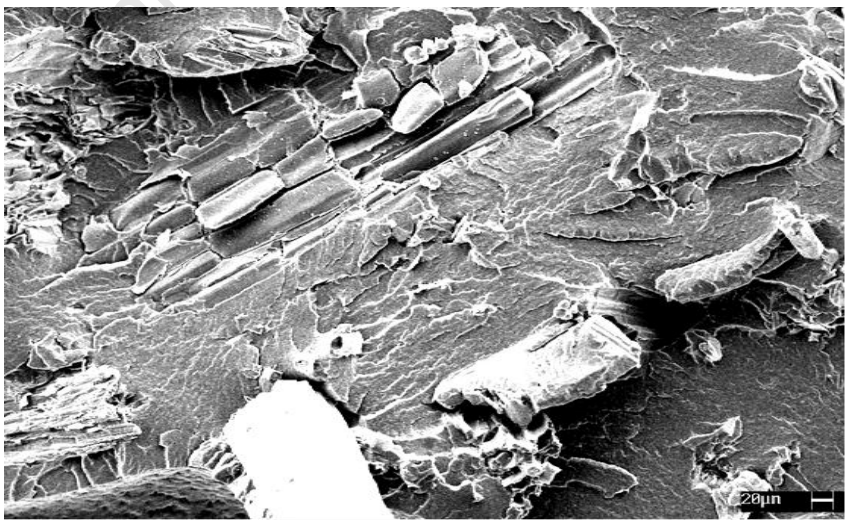

Figure 4.34 SEM micrograph of the fracture surface of kenaf bast20/core10/MAPP4 (wt %) PP composites

4.5.4 Effect of Moulding Process on Failure Mode

4.5.4.1 Effect on fibre direction

Figure 4.35 shows the fracture surface of injection moulded kenaf fibre reinforced PP composites. As expected, most fibres are oriented along the flow direction. The fracture surface of compression moulded composite, figure 4.36, shows anisotropic properties and fibres are oriented in an irregular fashion.

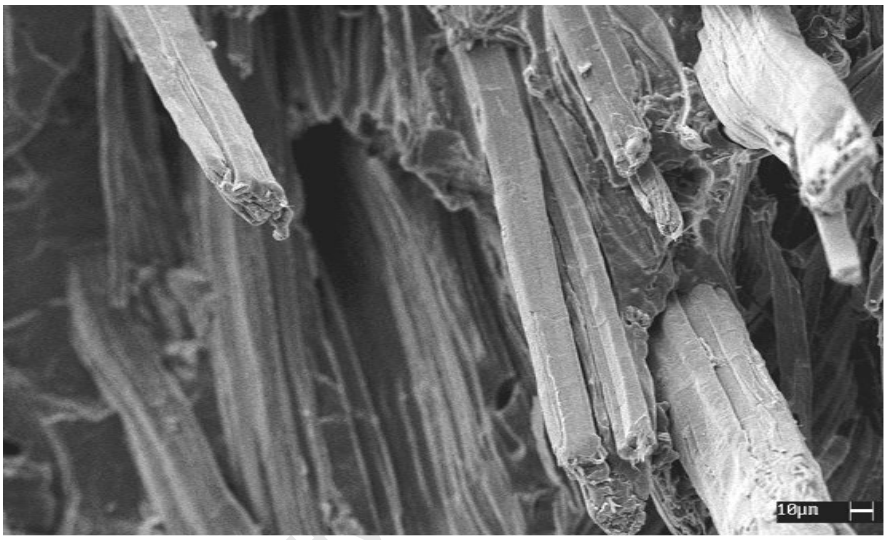

Figure 4.35 SEM micrograph of an injection moulded kenaf / PP composite fracture surface

Figure 4.36 SEM micrograph of a compression moulded kenaf / PP composite fracture surface

4.5.4.2 Effect on fibre length

Figure 4.37 and 4.38 show the effect of moulding process on the fibre length of the composites. Both SEM micrographs show 10 μm markers to compare the fibre length on the fracture surface. The fibre length of impact fracture surface of the injection moulded composite (Figure 4.37) was much shorter than that of the compression moulded ones (Figure 4.38).

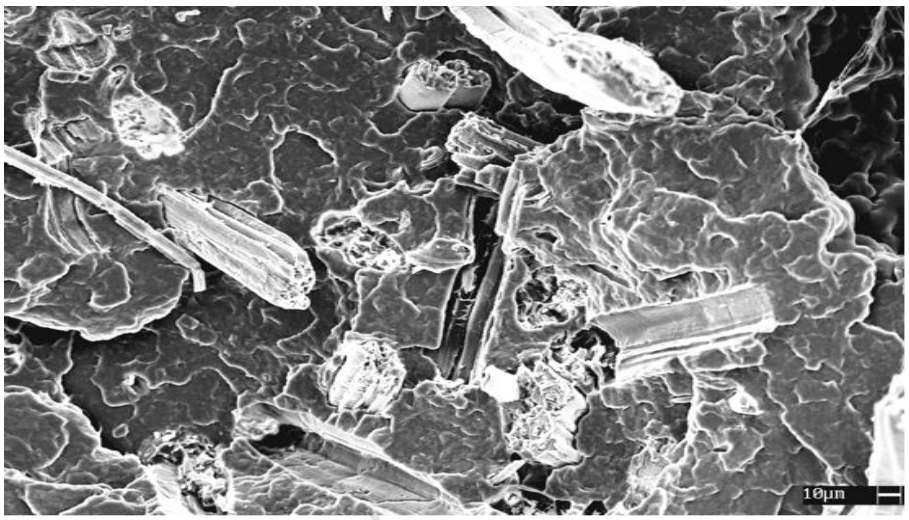

Figure 4.37 SEM micrograph of an injection moulded kenaf / PP composite fracture surface

Figure 4.38 SEM micrograph of a compression moulded kenaf / PP composites fracture surface

4.5.4.3 Effect on fibre surface and fibre-matrix adhesion

SEM micrographs show 10µm bars to compare the effects of moulding process on the fracture surface. Figure 4.39 shows the impact fracture surface of an injection moulded kenaf fibre reinforced PP composite. A rough fibre surface as well as signs of fibre-matrix adhesion was observed. On the other hand, the SEM micrograph of the compression moulded composite (Figure 4.40) shows a smooth fibre surface which indicates less adhesion between fibre and matrix.

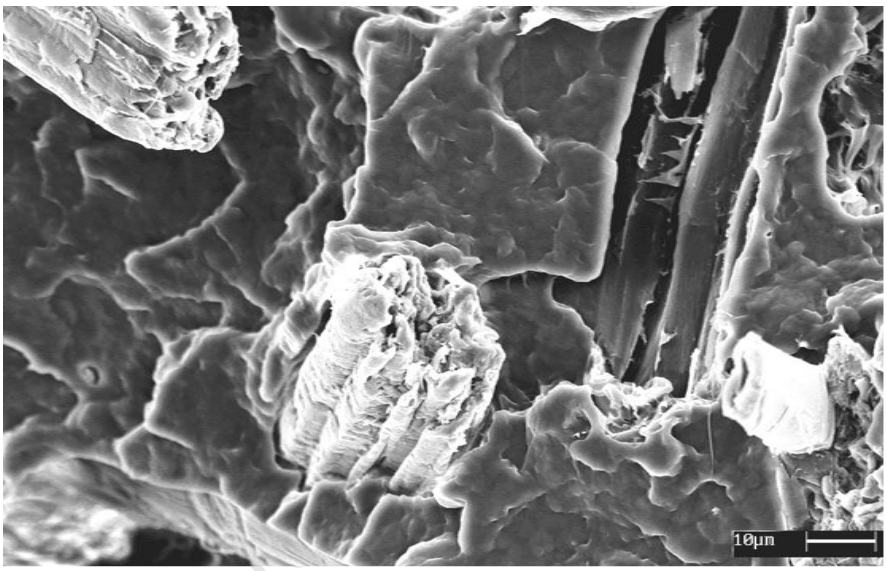

Figure 4.39 SEM micrograph of an injection moulded kenaf / PP composite

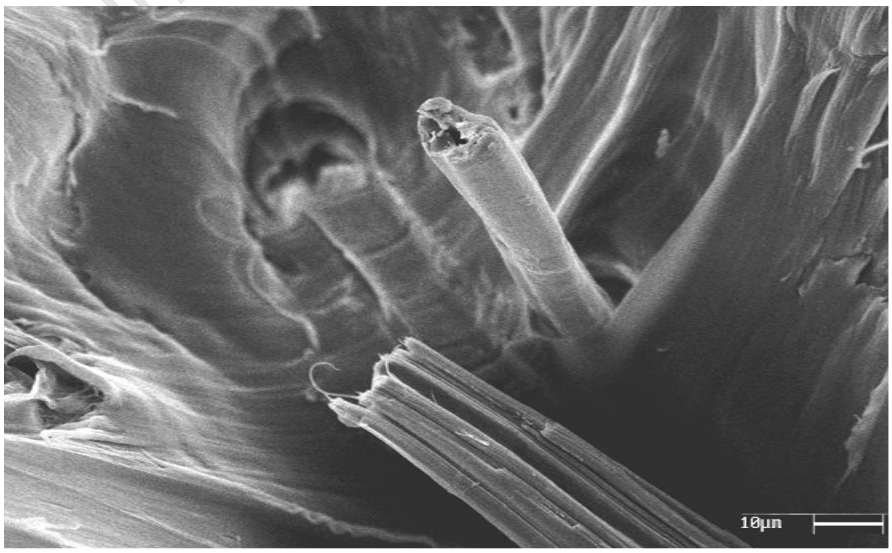

Figure 4.40 SEM micrograph of a compression moulded kenaf/PP composite

4.5.5 Effect of Testing Speed on the Failure Mode

4.5.5.1 Tested at 0.25 mm/min

Figure 4.41 shows a magnified fracture surface of the kenaf fibre reinforced PP composites tested in tension at a speed of 0.25 mm/min. The fracture end showed a rough surface. There was still an indication of fibre-matrix adhesion.

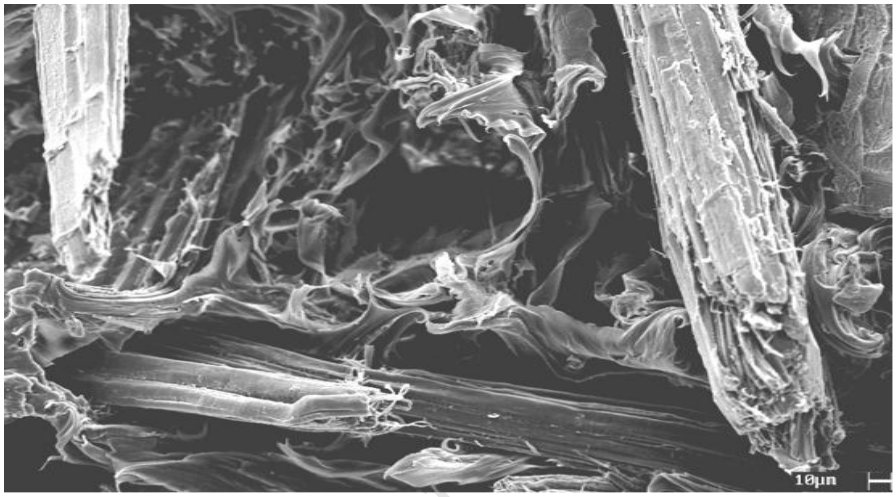

Figure 4.41 SEM micrograph of the kenaf / PP composite tested at 0.25 mm/min

4.5.5.2 Tested at 5 mm/min

Figure 4.42 shows a fracture surface of kenaf fibre reinforced PP composite tested under the test speed of 5 mm/min. The SEM results showed fibre bunch pull-out with signs of fibre-matrix adhesion.

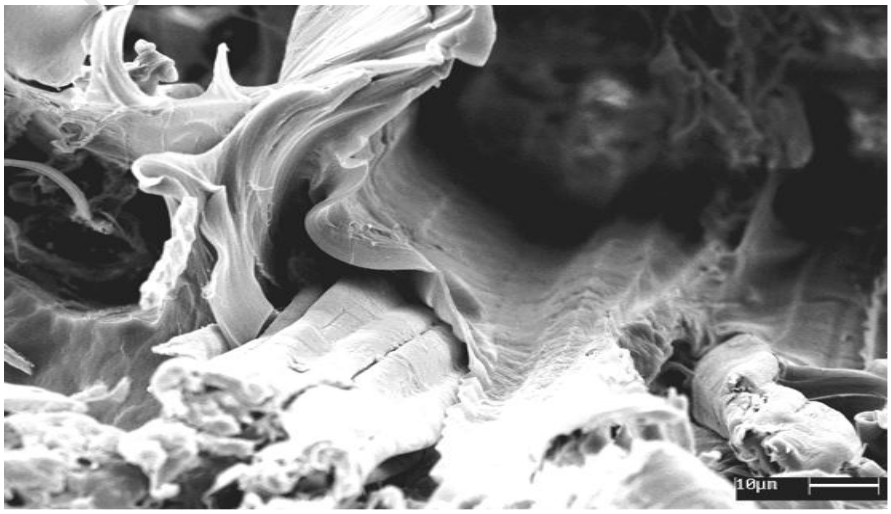

Figure 4.42 SEM micrograph of the kenaf / PP composite tested at 5 mm/min

4.5.5.3 Tested at 100 mm/min

Figure 4.43 shows the fracture surface of kenaf fibre reinforced PP composite tested at a speed of 100 mm/min. As expected, fibre bunch pull-out was observed. The smooth pulled out fibre surface indicates fibre-matrix debonding. Some degree of fibre-matrix adhesion was observed.

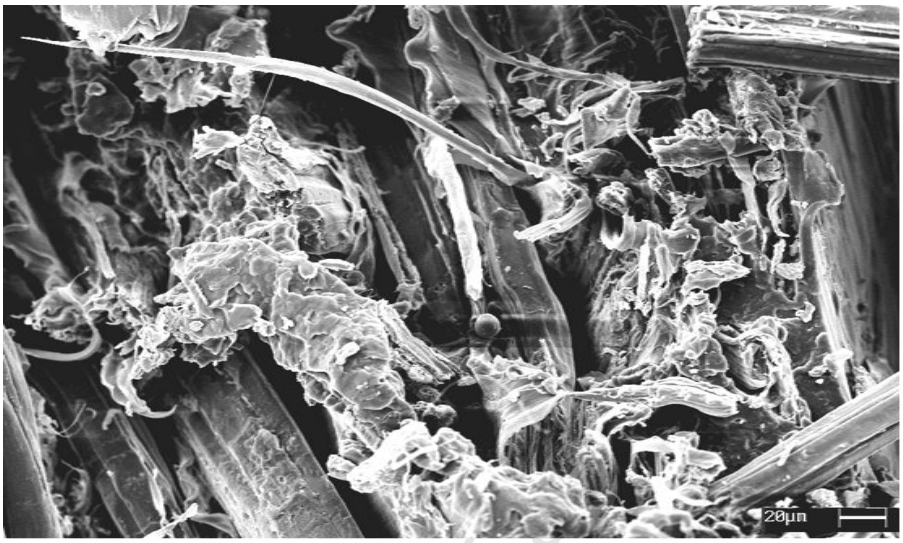

Figure 4.43 SEM micrograph of the kenaf / PP composite tested at100 mm/min

4.5.5.4 Tested at 200 mm/min

Figure 4.44 shows the fracture surface of kenaf fibre reinforced PP composite tested in tension at a cross- head speed of 200 mm/min. As expected, fibre bunch pull-out was observed. The exposed fibres indicate matrix delamination and debonding. Debonding resulted in cracking and disintegration of the matrix.

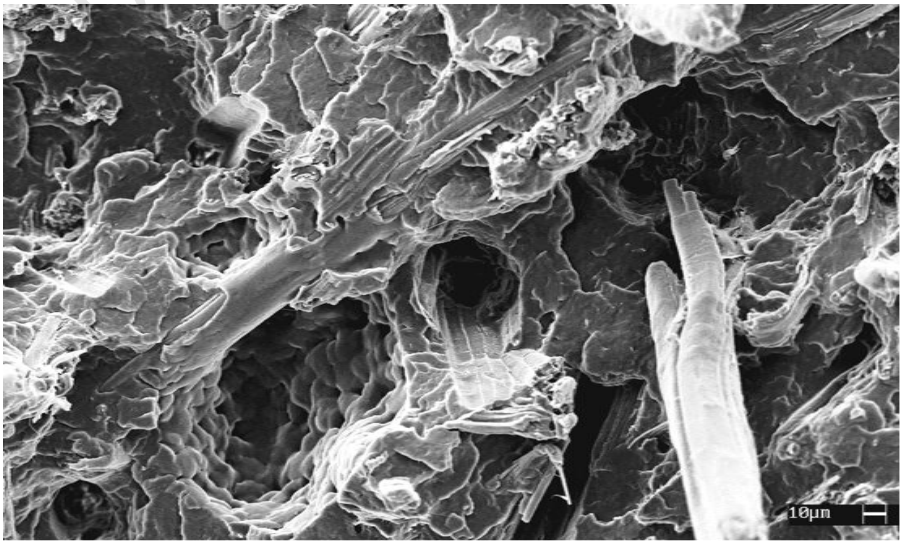

Figure 4.44 SEM micrograph of the kenaf / PP composite tested at 200 mm/min

4.5.6 International and Local Kenaf Fibres Fractography

The surfaces of the international and local kenaf bast fibres were taken with the SEM. As shown in figure 4.45, the continuous form of international fibres has a clean, smooth fibre surface. On the other hand, the local fibres (see figure 4.46) seem to have micro-cracks and little joints with many flakes on the fibre surface. These features eventually affect the mechanical properties of the PP composites.

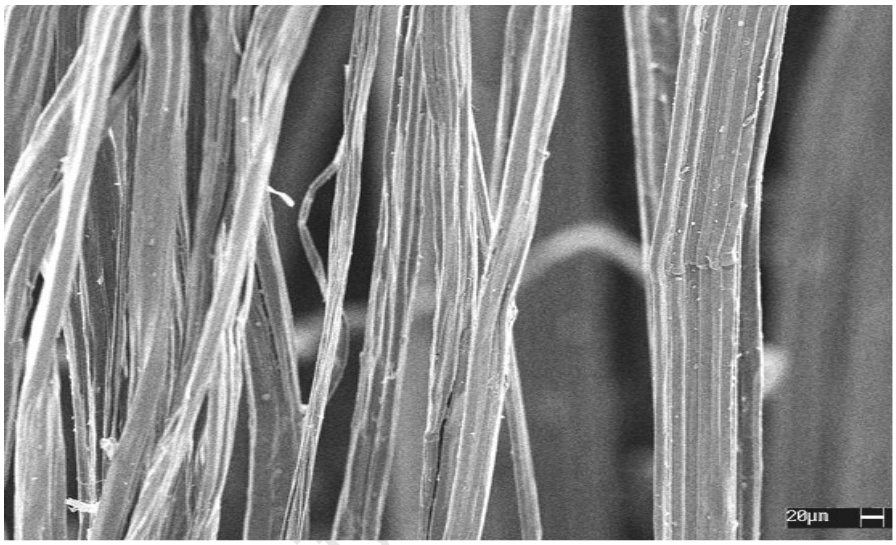

Figure 4.45 SEM micrograph of the international kenaf fibre surface

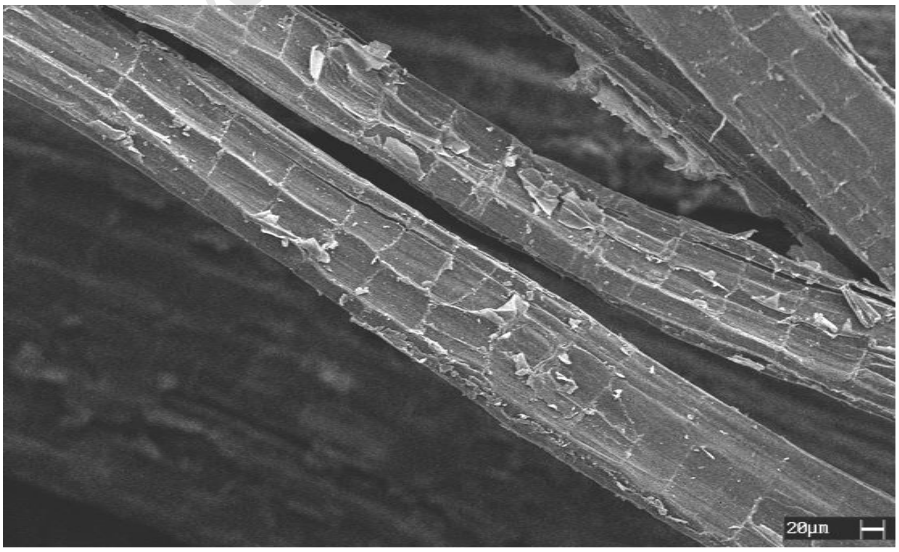

Figure 4.46 SEM micrograph of the local kenaf fibre surface

CHAPTER FIVE

DISCUSSION

5.1 INTRODUCTION

There are many parameters which might affect the mechanical and thermal properties of fibre reinforced thermoplastic composites. By studying the individual role or interplay between these parameters, an overall understanding of the properties of composite materials can be obtained. The following discussion explain how various parameters such as fibre content, coupling agent content, different processing methods, filler content (kenaf core) and different testing speeds influence the properties of kenaf fibre reinforced polypropylene composites.

This chapter is divided into the following sections:

- Effect of fibre content
- Effect of MAPP coupling agent content
- Effect of addition of kenaf core fibre as a filler material
- Effect of different processing methods
- Effect of different testing speed
- Comparing properties between local and international kenaf fibre reinforced polypropylene composites

In each section, the effects of the above parameters on the mechanical and thermal properties of kenaf fibre reinforced polypropylene composites are compared with the morphological changes observed on the fracture surface of the test specimens.

5.2 EFFECT OF FIBRE CONTENT ON THE PROPERTIES

5.2.1 Tensile, Flexural and Impact Analysis

The effects of fibre content on the mechanical properties of natural fibre reinforced thermoplastic composites have been studied and published in many papers [2-5]. Similar to those published works, both the tensile and flexural properties of the kenaf bast fibre reinforced polypropylene composites were found to be highly affected by increasing fibre content.

Figure 4.1 and figure 4.2 present the effect of fibre loadings (wt %) on the mechanical properties of kenaf fibre reinforced polypropylene composites. It shows that both tensile and flexural strength of the composites improved with increasing fibre content. It was clear from the graphs that the tensile and flexural strength of the kenaf fibre reinforced composites were higher than that of the unfilled polypropylene matrix. The increased tensile and flexural strength indicate that the incorporated kenaf fibres act as an efficient reinforcement for the PP matrix resin. Takashi et al [2] reported that the addition of kenaf fibres to the PP resin restrict the deformation of composites since the matrix resin was impregnated into the inter-fibrillar region. This resulted in good stress transfer from the matrix to the incorporated kenaf fibres. Table 4.1 shows that incorporation of 30% kenaf fibres into the PP matrix resulted in a maximum tensile strength. As mentioned earlier, incorporated kenaf fibres led to a better stress transfer between the fibre and the matrix. Hence, one might conclude that the optimum stress transfer from PP matrix to kenaf fibres occurs at 30% fibre loadings.

On the other hand, further increases of fibre content to 40% resulted in a significant decrease in tensile and flexural strength of the composites due to the insufficient filling of fibres into the matrix resin. At higher fibre loadings, fibre agglomeration and its pull out from matrix reduced the tensile strength. This caused poor compatibility between the fibre and the matrix which in turn resulted in an insufficient stress transfer from the matrix to the fibre.

Furthermore, incorporation of kenaf fibres into the PP matrix resulted in decreased impact resistance (see figure 4.3). This might be due to the limited mobilisation of macromolecule chains of PP matrix by the incorporated fibres. Incorporated kenaf fibres limit the ability of molecular chain movements and as a result, composites turned to be more brittle [61]. In other words, addition of fibres improved the interfacial bonding strength which resulted in harder and stronger composite materials. Hence, composites tend to fail by fibre breakage rather than fibre pull-out and this resulted in a substantial decrease in the impact resistance.

5.2.2 Thermal Analysis (DSC Analysis)

An investigation of the thermal stability of the kenaf fibre reinforced polypropylene composites was performed. Since the composite materials were subjected to an intense heat treatment during composite fabrication process, it was necessary to study the thermal stability and the thermal degradation process of composites [58]. For this purpose, differential scanning calorimetry (DSC) analysis was performed.

The effect of fibre content on thermal properties of the kenaf fibre reinforced polypropylene composites have been analysed by DSC. Table 4.13 shows the addition of kenaf fibres caused an increase in crystalline temperature as well as melting temperature of the composites. This increment was more noticeable with higher fibre contents. An increase in crystallisation temperature and melting temperature of the composites as a result of incorporation of fibres is in agreement with similar work done by Lopez-Manchado et al [59]. Increased crystallisation temperature explains a strong nucleation ability of the kenaf fibres in the polypropylene matrix [59].

It was observed from table 4.13 that the incorporated fibre contents were highly correlated with the degree of crystallinity as well as the amount of heat associated with fusion. As fibre content increased from 20% to 30%, it resulted in an increased degree of crystallinity as well as increased heat of fusion. On the other hand, further addition of fibres to 40% into the PP matrix, not only resulted in decreased degree of crystallinity but also resulted in decreasing the heat of fusion.

As mentioned earlier, increased degree of crystallinity can be explained by nucleating ability of the incorporated kenaf fibres. In other words, when 30% of kenaf fibres were added to the polypropylene matrix, the surface of kenaf fibres provided a sufficient number of nucleation sites to form crystallites. However, with further addition of kenaf fibres (to 40%) resulted in reduced degree of crystallinity. In fact, it was less than that of the 20% kenaf fibres incorporated into the composite. At 40% fibre loadings, although kenaf fibres provided some nucleation sites, it was not sufficient enough to increase the crystallinity in polymer matrix [58]. Besides, the decreased crystallinity could be caused by the dilution effect of kenaf fibres [59].

Birley et al [68] reported that the degree of crystallisation is highly influential on the mechanical properties of composites. Besides, Arbelaiz et al [58] mentioned that the addition of fibres affects the crystalline structure which resulted in changes of the mechanical properties of composites. This is in agreement with the results obtained in table 4.1-4.3 and table 4.13. It was found that increased degree of crystallinity caused increases in tensile and flexural strength but decreases in impact resistance. When the 30% kenaf fibres were incorporated into the PP matrix, the highest degree of crystallinity was obtained. At this point, the tensile and flexural strength of the composites also reached a maximum value while impact resistance showed a minimum value. On the other hand, a further increase of fibre contents higher than 30% caused the degree of crystallinity to decrease. This contributed to the minimum tensile and flexural strength but maximum impact resistance.

5.2.3 Morphological Analysis (SEM Analysis)

The effects of fibre content on the morphology of the impact fracture surface of the kenaf fibre reinforced PP composites were determined by scanning electron microscopy. As discussed earlier in section 5.2.1, incorporation of fibres into the PP matrix improved the tensile and flexural strength of the composites since the incorporated fibres restricted the deformation of composites [2]. The incorporated kenaf fibres acted as an efficient reinforcing agent and hence improved the stress transfer from the matrix to the fibre.

When the PP matrix was impregnated with 20% kenaf fibres, the incorporated fibres improved the interfacial bonding strength but it was not sufficient enough for an effective stress transfer to occur at interphase region. Poor stress transfer at the interphase region was shown as fibre bunch pull-out (see figure 4.28). The fibre-matrix debonding indicates poor fibre-matrix adhesion and river marks show the direction of crack propagation in the PP matrix.

When 30% kenaf fibres were added to the PP matrix, the composites had a maximum tensile and flexural strength. As shown in figure 4.29, the dominant failure mode of the composites with a strong interfacial bond was fibre breakage rather than fire pull-out. Delamination of the matrix indicates the occurrence of shear failure and rough fibre ends indicate that the material failed in a brittle manner.

On the other hand, when 40% kenaf fibres were added to the PP matrix, too high fibre content resulted in fibre agglomeration and led to poor compatibility at the interphase region. Consequently, fibres tend to pull out rather than break under the applied stress. As shown in figure 4.30, fibre pull-out was the dominant failure mode of the fibre reinforced composites at high fibre loadings. Additionally, micro-cracking on the fibre surface and rough fibre ends indicate brittle failure of material.

5.3 EFFECT OF MAPP CONTENT ON THE PROPERTIES

Although natural fibres have been used as efficient reinforcements due to its excellent specific properties, it requires surface modifications to improve the compatibility between the hydrophilic nature of natural fibres and the hydrophobic nature of the polymer matrix. There are many different types of coupling agents which has been used for improving the adhesion between lingo-cellulosic fibres and thermoplastic matrices [4, 33, 40, 41,48]. It is well known that maleic anhydride polypropylene (MAPP) can be effectively used as a coupling agent for polypropylene based composites [7, 8, 35, 60]. In this chapter, the effect of MAPP content on the mechanical, thermal and morphological properties of kenaf fibre reinforced polypropylene composites are reported.

5.3.1 Tensile, Flexural and Impact Analysis

As expected, increasing the amount of coupling agent resulted in a significant improvement in the tensile and flexural properties of the kenaf fibre reinforced PP composites. It is well known that MAPP functions efficiently for natural fibre reinforced polypropylene composites [7, 60]. According to Han et al [49], due to the thermodynamic segregation, MAPP is localised on the polar cellulosic fibre surface in the non-polar polypropylene matrix during processing the stage. Maleic anhydride (MA) present in the MAPP provides a polar interaction through the acid-base interaction and it covalently links to the hydroxyl group on the natural fibre [7]. Consequently, improved adhesion resulted in a more sufficient stress transfer from the matrix to the incorporated fibres. The efficient stress transfer is observed as increased tensile and flexural strength.

Figure 4.4 and figure 4.5 show that the addition of 2 to 4 (wt %) MAPP coupling agent resulted in a dramatic improvement in the tensile and the flexural properties of the kenaf fibre reinforced polypropylene composites. As mentioned earlier in section 2.4.5, the MAPP coupling agent reduced the amount of hydroxyl groups by acid-base reactions and hence reduced the tendency for moisture absorption.

On the other hand, when the kenaf fibres were modified with 5% MAPP coupling agent, it caused a significant decrease in the tensile and the flexural properties. This was due to insufficient stress transfer from the matrix to the fibres. As mentioned in section 2.4.5, poor fibre surface interface interactions could be caused by either (a) insufficient amount of MA present on MAPP which resulted in less formation of covalent linkages between the MA and the OH groups of kenaf fibres or, (b) insufficient length of MAPP which did not permit efficient chain entanglements with the polypropylene at the interphase region [35]. The chain entanglement between the MAPP and the non-polar polypropylene matrix is important since it highly affect the efficiency of stress transfer between the matrix and fibre [35]. Chain entanglements improve the stress transfer by acting as cross linkages from one chain to another entangled chain. Hence, one might conclude that the addition of 5% MAPP caused poor mechanical properties of the composites by forming an insufficient level of entanglements which in turn resulted in poor stress transfer from the matrix to the fibres.

As expected, increasing the MAPP content from 2% to 4% resulted in decreased impact resistance. This was caused by sufficient amount of MAPP which led to a stronger adhesion between the fibres and the matrix. This resulted in a better stress transfer at the interphase region. Stronger interfacial bond strength improved the tensile and the flexural strength but decreased the impact resistance. As the material becomes harder, its impact resistance decreases. On the other hand, when the fibres were modified with 5% MAPP coupling agent, insufficient stress transfer from the matrix to the fibre resulted in decreased tensile and flexural properties but a significant improvement in impact resistance.

5.3.2 Thermal Analysis (DSC Analysis)

The effect of surface modification on the thermal properties of kenaf fibre reinforced polypropylene composites were determined by employing DSC techniques. Table 4.14 shows that the addition of the coupling agent (MAPP) decreased the melting and the crystallisation temperatures of the composites. The decrease in melting temperature can be explained by presence of defects [60]. A lower crystallisation temperature indicates that the formation of crystallites in the polypropylene matrix occurred slowly. As the MAPP content increased, stronger interfacial bonds between the anhydride groups of MAPP/PP and the kenaf fibre were formed. This restricts the movement of macromolecules of the PP matrix and slows the formation of crystallites which showed as a lower crystallisation temperature. Furthermore, as shown by Feng et al [60], the anhydride groups of MAPP themselves could also form many defects in crystals by interrupting the regularity of polypropylene chains. Consequently, defects formed in crystals hinder the crystalline packing which resulted in a lower crystallisation temperature.

Although surface treatment on the kenaf fibres caused marginal changes in the melting and the crystallisation temperature of the composites, it has a significant effect on the mechanical properties. Besides, the mechanical properties of the composite are highly dependent on its crystalline structure which is greatly affected by surface treatment [58]. This is in agreement with the results obtained in figure 4.4-4.6. It was shown in figure 4.4 and 4.5 that a maximum tensile and flexural strength were obtained when fibres were modified with 4% MAPP coupling agent. Furthermore, table 4.14 shows that a maximum degree of crystallinity was also obtained when fibres were modified with 4% MAPP coupling agent. When kenaf fibres were modified with 4% MAPP coupling agent, the compatibility between the hydrophilic nature of kenaf fibres and the hydrophobic nature of polypropylene matrix reached the optimum point by the formation of strong covalent bonds as well as by acid-base reactions.

A sufficient amount of MAPP coupling agent (4%) improved the compatibility between kenaf fibres and the PP matrix and this resulted in the formation of perfect crystals in the polypropylene matrix. Consequently, it improved the mechanical properties of the composites as shown in the figure 4.4 and figure 4.5.

On the other hand, further increases of MAPP content to 5% caused a decrease in the degree of crystallinity. Up to a certain level, MAPP improved the adhesion between the fibre and matrix but any extra amount of MAPP act as a lubricant which tend to hinder the crystallisation packing. In other words, 5% MAPP modified composites had more amorphous regions than that of the 4% MAPP coupled composites. Besides, the composites modified with 5% MAPP coupling agent had a lower melting and crystallisation temperature than that of the composite modified with 4% MAPP coupling agent. Consequently, a lower degree of crystallinity resulted in the decreased mechanical properties.

5.3.3. Morphological Analysis (SEM Analysis)

The effect of surface treatment on the failure mode of kenaf fibre reinforced PP composites was studied by scanning electron microscopy. In figure 4.31, the SEM micrograph of the untreated kenaf fibre reinforced PP composites showed microscopic pits and cracks on the fibre surface which indicates a poor fibre-matrix interfacial bonding. On the other hand, surface modifications improved the compatibility between the hydrophilic nature of kenaf fibres and the hydrophobic nature of the polymer matrix. Hence, it resulted in improved adhesion between the fibre and the matrix. Good interfacial bonding between the fibre and the matrix was indicated with an arrow in the figure 4.32. Consequently, the improved adhesion resulted in better stress transfer from the matrix to the incorporated fibres. As shown in figure 4.32, the surface treated composites tend to fail by fibre breakage rather than fibre pull-out.

5.4 EFFECT OF ADDITION OF KENAF CORE FIBRES ON THE PROPERTIES

Along with kenaf bast fibres, kenaf core fibres have been used in various applications such as insulting materials, animal bedding materials and fibre boards [14]. It has been found that kenaf core has an excellent water/sound absorption property and thermal resistance [25]. This research work partly focused on the potential application of kenaf core as a filler material in the kenaf bast fibre reinforced polypropylene composites for automotive applications. As discussed earlier, kenaf bast fibres can be used efficiently as reinforcement for the thermoplastic based composites. The idea of using kenaf core fibres as filler material for automotive applications is still a developing area which requires an extensive research work to satisfy industrial requirements. As shown in the table 2.5, kenaf core fibres are much lighter than kenaf bast fibres. Hence, this investigation of the kenaf core fibres filled PP composites enabled producing of composites which are not only lighter than the bast fibre reinforced PP composites but also with similar mechanical properties.

In order to determine the potential usage of kenaf core as a filler material with similar or even superior mechanical properties than the bast fibre reinforced composites, test specimens were prepared as shown in table 3.2. In section 5.2 and 5.3, it was found that the 4% MAPP modified 30% kenaf bast fibre reinforced PP composite had optimum mechanical and thermal properties. Hence, the total filler content was kept at 30% and fibres were modified with 4% MAPP coupling agent. This chapter discusses the following three main topics:

1. Effect of incorporation of the kenaf core fibre (0 to 30%) into the PP matrix. (4% MAPP modified).
2. Effect of partial replacement of kenaf bast fibres with kenaf core fibres to produce lighter weight composites with similar mechanical and thermal properties to that of the bast fibre reinforced PP composites. (30% total filler content, 4% MAPP).

3. Effect of increasing the MAPP content to 6% to achieve an optimum property of the kenaf core filled kenaf bast fibre reinforced PP composites. (30% total filler content, 6% MAPP).

5.4.1 Tensile, Flexural and Impact Analysis

Figure 4.11 shows the effect of additions of kenaf core (35 meshed grains) on the flexural properties of the PP matrix. The flexural strength and flexural modulus of the polypropylene increased with increasing weight fraction of kenaf core fibres. As the core fibre content increased from 0 to 30%, there was an increase in the flexural strength and this increment was more significant with the flexural modulus. The presence of kenaf core improved stress transfer from the matrix to the filler/fibre which contributed to the improvement of flexural properties. This indicates that the kenaf core can be used as an efficient filler material in the PP matrix.

Also, the effect of additions of the core fibres into the bast fibre reinforced PP composites was investigated. As shown in figure 4.12, addition of core fibres resulted in improved flexural strength of the composites which had a total filler content of 30% (bast10/core20 and bast20/core10). This might be due to the dominant composition of the PP matrix in the system (70 wt %) which contributed to a strong and flexible blend. An improved flexural strength indicates efficient stress transfer from the matrix to the incorporated core filler fibre. On the other hand, addition of core fibres into the composites which had a total filler content higher than 30% (bast30/core20 and bast30/core30), resulted in the flexural strength decreasing with the incorporation of core fibres. The decreased flexural strength at too high filler content, 50% and 60%, could be caused by insufficient filling of fibres in the PP matrix which resulted in the incomplete adhesion between filler/fibres and matrix [62]. Hence, one might conclude that the 30% is the optimum filler content to obtain the maximum flexural strength of kenaf bast/core fibre reinforced composites.

Furthermore, the effects of the addition of core fibres on the tensile properties of PP composites were investigated. As shown in figure 4.14, incorporation of kenaf core fibres resulted in a decreased tensile strength as well as failure strain. Although 4% of MAPP coupling agents were applied to improve the adhesion between the non-polar PP matrix and the polar kenaf core fibres, it was not sufficient enough to improve the tensile strength. As the core content increased from 0 to 30%, there was a more significant decrease in tensile strength. This can be explained due to fibre agglomeration at higher filler loadings and its pull out from the PP matrix. Insufficient filling of the core fibres in the matrix resin caused poor adhesion between them. This in turn resulted in poor stress transfer from the matrix to the fibre and shown as decreased tensile strength.

Figure 4.14 shows the effects of partial replacement of kenaf bast fibres with kenaf core fibres on the tensile properties of PP composites. This replacement was attempted to produce a kenaf fibre reinforced PP composites with a lighter weight and so reduce the overall production costs. Based on the results obtained before, the total filler content was kept at 30% and the fibres were modified with 4% MAPP coupling agent to obtain good mechanical properties. Replacing 10% kenaf bast fibres with the core fibres (bast20/core10) reduced the tensile strength by 7.1%. When 20% of bast fibres were replaced with the core fibres (bast10/core20), the tensile strength was even further reduced by 30%. In both cases, the PP content was kept at the same level. This indicates that the kenaf bast fibres, instead of kenaf core fibres, play a dominant role as a reinforcement to maintain or to improve the tensile strength of the composites. Regardless of increasing core fibre content, reducing the bast fibre content resulted in a poor interfacial bonding strength and consequently resulted in decreased tensile strength.

Therefore a further attempt to increase the MAPP content to improve the adhesion between fibres and matrix was made. For this reason, fibres were modified with 6% MAPP coupling agent.

As shown in figure 4.15, increasing MAPP content to 6% resulted in a remarkable improvement in the tensile strength. The tensile strength of the composite modified with 6% MAPP increased to 33.6 MPa which was even higher than that of the 30% bast fibre reinforced PP composites. Increasing MAPP content improved the interfacial bonding strength between the non-polar, hydrophobic PP matrix and the polar, hydrophilic kenaf core fibres. The improved adhesion resulted in efficient stress transfer from the matrix to the fibres. Hence, one might conclude that a lighter weight of PP composites with good mechanical properties can be produced by replacing the bast fibres with lighter weight of core fibres as long as it is modified with a sufficient amount of MAPP coupling agent, which was found to be 6%.

Polypropylene has been considered as an outstanding polymer matrix due to its good mechanical performance, relatively low costs and easy processability. However, it has a limitation to be used widely as an engineering thermoplastic, for example, its relatively poor impact resistance. To improve the impact resistance of PP, kenaf core fibres were added to PP matrix. Figure 4.16 shows the effect of addition of kenaf core on the impact resistance of the PP matrix. According to Denac et al [63], addition of rigid organic fillers into the PP matrix resulted in improved strength, stiffness and abrasion resistance but it usually reduce impact resistance. On the other hand, in this research work, increasing filler content resulted in improved impact resistance but it was lower than that of the unfilled PP matrix resin. Fu et al [64] reported increasing impact resistance with incorporation of fillers indicates good adhesion between the incorporated filler fibres and matrix. Similarly, incorporation of core filler fibres improved the interface stress transfer from the matrix to the filler fibres which in turn showed as improved impact resistance.

Figure 4.18 shows the effects of kenaf core (powder) content on the flexural properties of the kenaf bast fibre reinforced PP composites. Kim et al [65] reported that the incorporation of micro-sized filler fibre fills micro-voids at the interphase region and improves the stress transfer through bridging. Nevertheless, as shown in figure 4.18, too high a filler content (50% and 60%) resulted in reduced flexural strength and flexural modulus. This might be caused by insufficient filling of the filler particles due to agglomeration.

5.4.2 Thermal Analysis (DSC Analysis)

The effect of the kenaf core fibre content on the thermal properties of the polypropylene matrix was determined by analysing the DSC scans. Table 4.15 shows that the addition of core fibres into the PP matrix caused a decrease in the crystallisation temperature (Tc) as well as melting temperature (Tm) of the PP matrix. As the core fibre contents increased from 0 to 30 (wt %), the melting temperature decreased by about 4ºC and this decrement was more noticeable with the crystallisation temperature which decreased by about 11.4 ºC. The decreased crystallisation temperature indicates a slower formation of crystallites in the PP matrix. This might be caused by the restricted mobilisation of polypropylene molecules due to the impregnated kenaf core fibres. Since kenaf core fibres were provided in 35 meshed grains, they were able to fill the micro-voids efficiently at the interphase region. Consequently, it improved the stress transfer from the PP matrix to the filler fibre [65]. This in turn reduced the movement of macromolecules within the PP matrix and slowed the formation of crystallites which was shown as a decreased crystallisation temperature. Furthermore, the addition of core fibres also resulted in a decreased melting temperature which indicates that there could be defects present in the composites.

It was observed from table 4.15 that the addition of core fibres resulted in a reduced amount of heat associated with fusion (ΔH_f) and degree of crystallinity (Xc). This might be caused by either insufficient amount of nucleation sites provided by the core fibres [58] or by dilution effect of the core fibres [59]. According to Arbelaiz et al [58], the addition of fibres has a high influence on the crystalline structure which causes changes in mechanical properties of a composite. This is in agreement with the results presented in table 4.15. As the addition of core fibre contents increased from 0 to 30%, ΔH_f as well as Xc decreased. Consequently, the tensile strength of the composites was decreased as shown in the table 4.12.

Additionally, the effects of the partial replacement of kenaf bast fibres with kenaf core fibres on the thermal properties of kenaf fibre reinforced polypropylene composites

were also investigated. Based on the results presented in table 4.1 and table 4.5, kenaf fibres were modified with 4% MAPP coupling agent and kept at 30% weight fraction of the composites. As expected, the Tm and Tc values of the 30% bast fibre reinforced PP composite (bast30) were higher than that of the composites in which bast fibres were partially replaced by core fibres (bast20/core10 and bast10/core20). The higher Tc and Tm of the 30% bast fibre reinforced composites indicate that the bast fibres have a dominant effect on the thermal properties of the composites. When the PP matrix was reinforced by the 30% bast fibres, the surface of bast fibres provided the most sufficient number of nucleation sites in the PP matrix. This resulted in an efficient stress transfer from the matrix to the incorporated fibres. Consequently, strong interfacial bonds were formed and it restricted the movement of the PP molecules. As a result, higher Tc and Tm values were obtained. The heat of fusion as well as degree of crystallinity was also at maximum values at 30% bast fibre loadings.

As more of bast fibres were replaced with core fibres (bast20/core10 and bast10/core20), a decrement of the heat of fusion and the degree of crystallinity were more significant. This is due to insufficient crystallites packing at the interphase region which might be caused by poor compatibility between the core filler fibres and the PP matrix. Although fibres were modified with 4% MAPP coupling agent, it was not sufficient enough to improve the adhesion between hydrophilic core fibres and hydrophobic PP matrix. On the other hand, when the fibres were modified by 6% MAPP coupling agent, Tm and Xc values of the bast20/core10 composite were improved significantly where they were even higher than that of the 30% bast fibre reinforced composites. At this MAPP content, the compatibility between the hydrophilic kenaf bast/core fibres and the hydrophobic PP matrix reached a maximum level. Consequently, strong interfacial bonding strength restricted the movement of macromolecules and resulted in higher Tm values.

From the above discussions, one might conclude that a lighter composite material could be obtained by partially replacing the bast fibres with lighter core fibres. However, to achieve similar or even superior thermal and mechanical properties than that of the 30% bast fibres reinforced composites, it needs to be modified with 6% MAPP coupling agent.

5.4.3 Morphological Analysis (SEM Analysis)

The effect of an addition of core fibres on the morphology of impact fracture surface of the 20% bast fibre reinforced PP composite was determined by scanning electron microscopy. Figure 4.33 shows a SEM micrograph of the fracture surface of the 20% kenaf bast fibre reinforced PP composites. Bunch of fibre pull-out was observed. Delamination of the matrix indicates the occurrence of shear failure and the rough fibre ends indicate that the material failed in a brittle manner. Figure 4.34 presents a SEM micrograph of fracture surface of the kenaf bast20/core10 filled PP composites. The addition of core fibres resulted in a decreased tensile strength but increased impact resistance. This was in agreement with the SEM micrographs observed. In figure 4.34, debonding was observed due to the fibre pull-out. Kenaf core debonding resulted in cracking and disintegration of the matrix. Furthermore, delamination was also observed which indicates a poor fibre-matrix interfacial bond.

5.5 EFFECT OF MOULDING PROCESS ON THE PROPERTIES

Extrusion followed by injection moulding causes changes in the length and diameter distribution of incorporated fibres [54]. Consequently, the properties of the composite materials are affected. On the other hand, extrusion followed by compression moulding neither damaged nor changed the distribution of fibres. Hence, compression moulding process reduces the changes in physical properties of natural fibres by restricting the molecular relaxation [54].

5.5.1 Flexural and Impact Analysis

As shown in figure 4.7 and figure 4.8, the flexural properties of the composite materials were clearly influenced by the types of moulding process. Injection moulded composites had a higher value of flexural strength and flexural modulus compared with that of the compression moulded composites. Injection moulded composites improved the fibre dispersion hence increased the flexural strength of composites.

According to Liu et al [54], a compression moulded composite generally has a higher modulus than that of an injection moulded composite since the compression moulding preserve isotropic properties of the composite. Unlike the results reported in Liu's paper, the flexural modulus of the compression moulded composite was much lower than that of the injection moulded composites (see figure 4.8). The properties of the compression moulded composite are highly related to a consolidation of the composite, which depends on the processing conditions as well as the types of moulder which was used during processing. Liu et al [54] stated that a closed mould is better at transmitting pressure to the composites which resulted in a better consolidation of the composite than that of an open picture frame mould. Consequently, in a closed mould, the modulus does not change with different processing methods. In this project, however, an open picture frame mould was used. Unexpectedly, as shown in figure 4.8, the injection moulded composite had a higher modulus than that of the compression moulded composite with an open frame mould.

According to Liu et al [54], this divergence was caused by the mould type. In a picture frame mould, compression moulding cannot keep pressure on the composite which possibly causes poor consolidation of the composite. This resulted in a lower modulus.

Figure 4.9 presents the effect of moulding process on the Charpy impact resistance of the kenaf fibre reinforced polypropylene composite. The impact resistance of the compression moulded composites were much higher than that of the injection moulded composites at 20% fibre loadings. The higher impact resistance of the compression moulded sample may be explained by a sufficient fibre bridging effect through fibre pull out [54]. During compression moulding, the kenaf fibres were able to maintain the same fibre orientation and length. Consequently, it resulted in a greater bridging effect for the compression moulded sample than the injection moulded sample. On the other hand, there was a bigger chance of fibre damage during extrusion and injection moulding process. This resulted in a less fibre bridging effect and showed as decreased in the impact resistance.

Since the impact resistance of compression moulded sample was higher than that of injection moulded sample, one might conclude that: (a) the tensile and flexural strength of the composite is highly depend on the interfacial bond strength. However, the tensile and flexural strength of the injection moulded samples were higher than that of the compression moulded sample. This suggests that fibre breakage dominates the failure mode of composites and affects the tensile and the flexural strength. However, (b) the impact resistance of the composite was highly dominated by fibre bridging effects which mainly occurred in the compression moulded sample compared to fibre breakage which dominated injection moulded sample.

5.5.2 Morphological Analysis (SEM Analysis)

The morphology of the impact fracture surface of kenaf fibre reinforced PP composite was investigated by scanning electron microscopy. It was observed that a compression and an injection moulding had different effects on the fibre orientation of the composites.

SEM micrographs for the injection moulded samples showed that most of the fibres were oriented along the flow direction where as micrograph of the compression moulded samples showed a random arrangement of fibres (see figure 4.35 and 4.36). In both micrographs, however, there was a certain degree of interaction between the matrix and the fibre.

By observing the micrographs, the degree of adhesion between the fibre and the matrix as well as the failure mechanism could be identified. Figure 4.39 and 4.40 show the SEM micrographs of impact fracture surface of the compression moulded and the injection moulded samples.

As shown in figure 4.39, injection moulded samples had a rough fibre surface which indicates a good interphase bonding between the fibre and the matrix while compression moulded samples showed a smooth fibre surface which indicates poor adhesion. As mentioned earlier, the good interphase bonding of the injection moulded samples results in sufficient stress transfer from the matrix to the fibre which in turn resulted in improved tensile and flexural strength. Hence, SEM micrographs of the rough fractured surface of the injection moulded tensile specimens are matched with the improved tensile strength.

On the other hand, the impact resistance of the compression moulded composite was higher than that of the injection moulded composite. As mentioned earlier in section 5.4.1, the higher impact resistance of the compression moulded sample is due to the fibre bridging effect through fibre pull-out. This was observed in the SEM micrographs (see figure 4.39). The micrographs showed that the injection moulded sample had a good interaction between the fibre and the matrix. Its fibre pull-out effect, however, was lower than that of the compression moulded sample and this resulted in a smaller fibre bridging effect in injection moulded samples. Consequently, injection moulded sample with a stronger interfacial bonding failed with fibre breakage rather than fibre pull-out.

5.6 EFFECT OF TESTING SPEED ON THE PROPERTIES

5.6.1 Tensile Analysis

Figure 4.10 presents the effects of testing speed on the tensile properties of the kenaf fibre reinforced polypropylene composites. It can be seen that increasing test speed led to an increase in the tensile strength. The tensile strength of the composite at different test speeds was evaluated. Test speeds of 200 mm/min were taken as the maximum testing speed. It has been reported that the mechanical properties of fibre reinforced composites not only depend on the constituents (fibre and matrix) but also depends on the interfacial bonding strength [66]. This suggests that there was stronger interfacial boding between the kenaf fibres and the PP matrix at testing speeds of 200 mm/min. A strong interfacial bond contributes to a better transmitting of load from the matrix to the fibres which in turn showed as a greater tensile strength. It is known that at high strain rates molecular untanglement is difficult leading to breakage of polymer chains rather than chain slippage and this effect also contributes to the higher strengths observed.

5.6.2 Morphological Analysis (SEM Analysis)

Figure 4.41-4.44 presents the effects of test speed on the morphology of the fracture surface of the impact test specimens. The morphology of fracture surface showed various forms of internal failures such as fibre breakage, fibre pull-out, debonding, matrix micro-cracking and delamination. From the SEM micrographs, bunches of fibre pull-out was observed with increasing cross-head speed. This suggests that the fibre-matrix interfacial bonding strength was greater than the tensile failure strength of the composite at high strain rates (100 mm/min and 200 mm/min). Figure 4.44 showed the fibre bunch pull-out with smooth fibre surfaces which indicates fibre-matrix debonding [36]. When a strong interfacial bond exists between the fibre and the matrix, cracks do not propagate along the length of fibre but rather tend to propagate across the fibre. This leads to fibre pull-out instead of fibre breakage enabling the fibres to remain as an effective reinforcement even after the fibre breaks [36].

5.7 LOCAL VS. INTERNATIONAL KENAF/PP COMPOSITES

Table 4.12 presents a comparison of flexural strength, flexural modulus and impact resistance between the local and the international kenaf fibre reinforced polypropylene composites. For all the mechanical properties observed, international kenaf fibre reinforced composite showed a superior strength and modulus compared to that of the local kenaf fibre reinforced composite. The superior mechanical properties of the international kenaf fibre reinforced composites could be due to the degree of adhesion at the interphase region. As shown in figure 4.45, the international kenaf fibres have continuous form of clean and smooth fibre surface. On the other hand, local fibres seem to have many micro-cracks and little joints with many flakes on the fibre surface (see figure 4.46). This could interrupt the adhesion between fibres and PP matrix and resulted in less stress transfer from the matrix to the fibres. As a result, the flexural strength and impact resistance of the local kenaf fibre reinforced PP composites were lower than that of the international kenaf fibre reinforced PP composites. Since the differences are only marginal, one might conclude that the flexural properties and the impact strength of local kenaf fibre reinforced composites are on par with the international kenaf fibre reinforced composites.

5.8 ACCEPTABILITY OF THE EXPERIMENTAL RESULTS

There are many factors which affect the properties of composite materials such fibre and matrix quality including homogeneity, interfacial adhesion, applied composite fabrication process and tooling equipment. The reliability of the experimental results is calculated as follows:

To determine how the measured experimental data are "reasonably confident", firstly, the discrepancy between the expected value and the X_{best} values are calculated from equation 5.1 below.

$$\text{Discrepancy} = \left| X_{best} - X_{exp} \right| \qquad (5.1)$$

Where X_{exp} denotes the average ultimate tensile strength and X_{best} denotes the best UTS value.

Then, the number of standard deviation, t, by which X_{best} differs from X_{exp} (here, σ denotes the standard deviation) is calculated from equation 5.2 below.

$$t = \frac{\left| X_{best} - X_{exp} \right|}{\sigma} \qquad (5.2)$$

Next, from the table of the normal error integral, we can find the probability of obtaining an answer that differs from X_{exp} by t or more standard deviations.

Probability (outside tσ) = 100% - Probability (within tσ) (5.3)

5.8.1 Analysis of the Tensile Test Results

Table 5.1- Table 5.5 summarise the average ultimate tensile strength and standard deviations of the kenaf fibre reinforced polypropylene composites. During tensile testing, five tests were performed for each batch of the composites. The average ultimate tensile strength ($\overline{X}$) of the composite with the smallest standard deviation was used as X_{best}. From the equation 5.2, the number of standard deviations, t, was calculated and from that, the probability was determined by utilising the equation 5.3.

Table 5.1 Effect of fibre content on tensile test results

Fibre Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
20	31.6	30.87	0.58
30	35.2	34.22	0.05
40	23.3	20.13	0.37

From the selected data, t was calculated to be 1.26 and the probability (outside 1.26σ) was 79.2%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 79.2%.

Table 5.2 Effect of MAPP content on tensile test results

MAPP Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
2	31.6	29.21	0.31
3	36.5	35.55	0.32
4	40.4	37.65	0.42
5	35.1	34.95	0.53

From the selected data, t was calculated to be 2.97 and the probability (outside 2.97σ) was 99.7%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 99.7%.

Table 5.3 Effect of kenaf core content on tensile test results

Fibre Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
Core10	26.34	25.52	0.09
Core20	24.97	24.38	0.74
Core30	25.16	25.12	0.46
Core20/Bast10	25.16	24.48	0.63
Core10/Bast20	30.62	30.59	0.63
Core10/Bast20/Mapp6	33.62	33.34	0.21

From the selected data, t was calculated to be 1.33 and the probability (outside 1.33σ) was 81.65%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 81.65%.

Table 5.4 Effect of testing speed on tensile test results

Testing Speed (mm/min)	$\overline{X}$	X_{best}	$\sigma_{\times}$
0.25	28.45	26.29	0.44
5	32.70	32.65	0.44
100	37.46	36.21	0.33
200	41.14	40.20	1.73

From the selected data, t was calculated to be 3.79 and the probability (outside 3.79σ) was 99.95%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 99.95%.

Table 5.5 Effect of moulding process on tensile test results

Moulding	Composite	$\overline{X}$	X_{best}	$\sigma_{\times}$
Injection	Kenaf30/ MAPP2	63.9	62.82	0.38
Compression	Kenaf30/ MAPP2	57.3	56.49	0.55

From the selected data, t was calculated to be 2.84 and the probability (outside 2.84σ) was 99.55%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 99.55%.

5.8.2 Analysis of the Flexural Test Results

Table 5.6- Table 5.8 summarise the average flexural strength and standard deviation of the kenaf fibre reinforced polypropylene composites. During flexural testing, five tests were performed for each batch of the composites. The average flexural strength ($\overline{X}$**)** of the composite with the smallest standard deviation was used as X_{best} . From the equation 5.2, the number of standard deviations, t, was calculated and from that, the probability was determined by utilising the equation 5.3.

Table 5.6 Effect of fibre content on flexural test results

Fibre Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
0	49.3	48.29	0.51
20	56.5	55.25	0.73
30	57.3	57.21	0.55
40	60.6	59.21	0.34

From the selected data, t was calculated to be 4.08 and the probability (outside 4.08σ) was 99.99%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 99.99%.

Table 5.7 Effect of MAPP content on flexural test results

MAPP content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
2	63.9	60.28	0.28
3	64.6	62.39	0.13
4	66.9	65.82	0.13
5	63.5	63.52	0.07

From the selected data, t was calculated to be 1.71 and the probability (outside 1.71σ) was 91.27%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 91.27%.

Table 5.8 Effect of core content on flexural test results

Core Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
10	44.85	44.36	0.63
20	44.06	44.25	0.43
30	46.16	46.05	0.22
Core20/Bast10	49.24	47.28	0.23
Core10/Bast20	53.08	52.92	0.13
Core10/Bast20/MAPP6	56.94	55.71	0.21

From the selected data, t was calculated to be 1.23 and the probability (outside 1.23σ) was 78.13%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 78.13%.

5.8.3 Analysis of the Impact Test Results

Table 5.9- Table 5.11 summarise the average impact resistance and standard deviation of the kenaf fibre reinforced polypropylene composites. During impact testing, five tests were performed for each batch of the composites. The average impact resistance ($\overline{X}$) of the composite with the smallest standard deviation was used as X_{best}. From the equation 5.2, the number of standard deviations, t, was calculated and from that, probability was determined by utilising the equation 5.3.

Table 5.9 Effect of fibre content on impact resistance

Fibre Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
20	6.82	6.69	0.24
30	4.48	4.35	0.26
40	2.97	2.75	0.81

From the selected data, t was calculated to be 0.54 and the probability (outside 0.54σ) was 41.08%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 41.08%.

Table 5.10 Effect of MAPP content on impact resistance

MAPP Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
2	3.95	3.85	0.03
3	3.92	4.01	0.02
4	3.91	4.23	0.06
5	4.49	5.25	0.04

From the selected data, t was calculated to be 4.5 and the probability (outside 4.5σ) was 99.99%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 99.99%.

Table 5.11 Effect of core content on impact resistance

Fibre Content (wt %)	$\overline{X}$	X_{best}	$\sigma_{\times}$
Core10	2.36	2.23	0.04
Core20	2.41	2.56	0.11
Core30	2.89	3.01	0.23
Core20/Bast10	3.11	3.01	0.04
Core10/Bast20	3.45	3.20	0.05

From the selected data, t was calculated to be 0.91 and the probability (outside 0.91σ) was 63.72%. Hence, the probability that the next tensile strength would lie within the distribution of the average is 63.72%.

CHAPTER SIX

CONCLUSIONS

The work carried out during the course of this research has contributed to our understanding of the factors governing the properties of kenaf fibre reinforced polypropylene composites. In particular the following conclusions are noteworthy:

1. Increasing the kenaf bast fibre content resulted in a significant increase in the tensile and flexural strength but had a detrimental effect on the impact resistance of the composites. The incorporation of the 30% kenaf fibres into the polypropylene matrix resulted in a maximum tensile, flexural strength and modulus but with a minimum impact resistance.
2. The incorporation of bast fibres resulted in improved thermal properties of the PP matrix. The melting, crystallisation temperatures as well as the degree of crystallinity marginally increased with the addition of fibres. At 30% fibre loading, the thermal properties reached the maximum point but it reduced with further additions of fibres.
3. A 4% MAPP coupling agent was the most suitable coupling agent content since it resulted in a maximum tensile, flexural strength and modulus. The thermal parameters such as melting temperature, crystallisation temperature, heat of fusion and degree of crystallinity also reached a maximum value at this MAPP content.
4. As the composite material become stronger, the dominant failure mode of the composite was fibre breakage rather than fibre pull-out.
5. An optimum in mechanical and thermal properties of composite were obtained when the 4% MAPP modified with 30% kenaf bast fibres were incorporated into the PP matrix.
6. The partial replacement of bast fibres with kenaf core fibres enables the production of a lighter composite. When 6% MAPP modified with 10% of bast fibres were replaced by core fibres (bast20/core10), its mechanical and thermal properties were even higher than that of the 30% bast fibre reinforced polypropylene composites.

7. The flexural and impact strength of the local kenaf fibre reinforced composites were found to compare well with those of the international kenaf fibre reinforced composites.

The overall effect of some of the variables studied is summarised in the table below:

Property	↑ Bast Fibre Content		↑ MAPP Content		↑ Core Fibre Content	Moulding Process
	< 30%	> 30%	< 4%	> 4%		Inj vs. Comp.
Tensile Strength	↑	↓	↑	↓	↓	>
Flexural Strength	↑	↓	↑	↓	↑	>
Flexural Modulus	↑	↓	↑	↓	↑	>
Impact Resistance	↓	↑	↓	↑	↓	<
% Elongation	↓	↑	↓	↑	↓	-
Tm	↑	↓	↑	↓	↓	-
Tc	↑	↓	↑	↓	↓	-
Xc	↑	↓	↑	↓	↓	-

CHAPTER SEVEN

RECOMMENDATIONS

1. Local kenaf fibre was found to compare favourably with those of the international kenaf fibres. It was clear from this research work that the local kenaf fibre could be used as an efficient reinforcement for polypropylene matrix composites. It can be concluded that the initial findings are promising but it still need further research to develop new technologies for producing finer and clean fibres.

2. Kenaf core fibres were found to be an efficient filler material. There is not much published data on the mechanical, thermal and dynamic mechanical properties of kenaf core fibre filled composites. The characteristics of these composites should be researched further for environmental-economic advantages.

CHAPTER EIGHT

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